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**A review of structural patterns and melting processes in the
Archean craton of West Greenland: Evidence for crustal growth at
convergent plate margins as opposed to non-uniformitarian models**

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Abstract

The Archean craton of West Greenland consists of many fault-bounded Eoarchean to Neoarchean tectonic terranes (crustal blocks). These tectonic terranes are composed mainly of tonalite-trondhjemite-granodiorite (TTG) gneisses, granitic gneisses, metavolcanic-dominated supracrustal belts, layered anorthositic complexes, and late- to post-tectonic granites. Rock assemblages and geochemical signatures in these terranes suggest that they represent fragments of dismembered oceanic island arcs, consisting mainly of TTG plutons, tholeiitic to calc-alkaline basalts, boninites, picrites, and cumulate layers of ultramafic rocks, gabbros, leucogabbros and anorthosites, with minor sedimentary rocks. The structural characteristics of the terrane boundaries are consistent with the assembly of these island arcs through modern style of horizontal tectonics, suggesting that the Archean craton of West Greenland grew at convergent plate margins. Several supracrustal belts that occur at or near the terrane boundaries are interpreted as relict accretionary prisms. The terranes display fold and thrust structures and contain numerous 10 cm to 20 m wide bifurcating, ductile shear zones that are characterized by a variety of structures including transposed and redistributed isoclinal folds. Geometrically these structures are similar to those occurring on regional scales, suggesting that the Archean craton of West Greenland can be interpreted as a continental scale accretionary complex, such as the Paleozoic Altaids. Melting of metavolcanic rocks during tectonic thickening in the arcs played an important role in the generation of TTGs. Non-uniformitarian models proposed for the origin of Archean terranes have no analogs in the geologic record and are inconsistent with structural, lithological, petrological and geochemical data collected from Archean terranes over the last four decades. The style of deformation and generation of felsic rocks on outcrop scales in the

Archean craton of West Greenland and the Mesozoic Sulu orogenic belt of eastern China are similar, consistent with the formation of Archean continental crust by subduction zone processes.

Keywords: West Greenland, Archean tectonics, Convergent margins, Shear zone, Accretionary complex, Sulu Orogen

1. Introduction and scope

Generation and destruction of Earth's continental and oceanic crusts in the Phanerozoic Eon have been coupled with the Wilson cycle of plate tectonics (Oreskes, 2003). Phanerozoic continental crust has been produced at convergent plate margins mainly through tectonic accretion and emplacement of mantle-derived igneous rocks (Şengör et al., 1993, 2014; Burke, 2011). The main driving force behind present-day structural, magmatic, sedimentary and metamorphic processes involved in the formation and evolution of the continental crust is plate tectonics, resulting from the flow of matter and energy between the lithosphere and asthenospheric mantle along divergent, convergent, and transform plate boundaries (Şengör, 1990; Oreskes, 2013; Polat, 2014).

Nearly all geologists accept the idea that the Phanerozoic evolution of the Earth has been shaped by plate tectonic processes. However, when it comes to the interpretation of the style of tectonic processes and growth of the continental crust in the Precambrian, particularly in the Archean Eon, the opinions of geologists diverge. Despite growing lines of field, geochemical, geophysical and theoretical evidence indicating that the Earth has evolved through Phanerozoic-like plate tectonic processes at least since 3.8 Ga and that Archean continents originated mainly at convergent plate margins (see Windley, 1993; Kusky and Polat, 1999; Polat et al., 2002;

Furnes et al., 2007, 2013; Garde, 2007; Nutman et al., 2009, 2013, 2015a; Nebel-Jacobsen et al., 2010; O’Neil et al., 2011; Adam et al., 2012; Amiguet et al., 2012; Kisters et al., 2012; Nagel et al., 2012; Arndt, 2013; Santosh et al., 2013; Wang et al., 2013; Turner et al., 2014; Kusky et al., 2014), the nature of tectonic processes that generated Archean terranes continues to be debated (e.g., Hamilton, 1988, 2013; Stern, 2005; Bédard, 2006; Robin and Bailey, 2009; Johnson et al., 2014; Thébaud and Rey, 2013; Moore and Webb, 2013; François et al., 2014; Gerya, 2014; Dyck et al., 2015; Kamber, 2015). In regards to the evolution of the Earth in the Archean, the following questions are hotly debated: How far back in Earth history were geological processes driven by plate tectonics? Were Archean crust-forming processes dominated by density-driven, vertical crustal overturns, diapirs, drips, residue delaminations, and volcanic heat pipes without any modern analogs? How did Archean greenstone belts form? Are Archean greenstone belts and associated layered anorthosite complexes fragments of ophiolites? How did Archean continents grow? Answers to all these questions remain elusive and controversial.

In this paper, we present new field data from Eoarchean to Neoarchean terranes in West Greenland (Fig. 1), showing that the geometry and style of outcrop scale structures (e.g., fold patterns) in shear zones are remarkably similar to those of regional-scale structures. We discuss the importance of these similarities and their tectonic significance for the growth of Archean continental crust. Then, we compare these Archean structures and the formation of Archean felsic rocks (TTGs: tonalite, trondhjemite, granodiorite suites, granites) with those in the Mesozoic Sulu orogen, eastern China, to address the above questions and revisit the tectonic models proposed for the origin of Archean crust. Given the fact that all rocks in the Archean craton of West Greenland (also known as the North Atlantic craton) have been variably metamorphosed, the prefix ‘meta’ will be taken as implicit.

2. Archean geological record in West Greenland

The Archean craton of West Greenland contains the world's best exposed rocks from the interval ranging in age from 3850 to 2550 Ma, providing an excellent opportunity to study the early evolution of the Earth (Fig. 1). The craton has a very complex geologic history characterized by multiple phases of magmatic, structural and metamorphic events that took place between 3850 and 2550 Ma (see McGregor, 1973; Bridgwater et al., 1974, Kamber and Moorbath, 1998; Friend and Nutman, 1991; 2005a, 2005b, 2015a, 2015b; Nutman and Friend 2009; Windley and Garde, 2009). Presenting a detailed account of these geological events is beyond the scope and objective of this contribution.

The Archean craton in West Greenland consists mainly of Eoarchean to Neoarchean (ca. 3850-2700 Ma) orthogneisses with TTG compositions and 3660-2550 Ma granitic rocks (Nutman et al., 2004, 2013; Steenfelt et al., 2005, Windley and Garde, 2009; Hoffmann, 2014). The orthogneisses (ca. 65%) and granites (ca. 15%) constitute ca. 80%, whereas the supracrustal rocks and layered anorthositic complexes form ca. 20% of the craton (Fig. 1) (Kalsbeek and Myers, 1973; Wedepohl et al., 1991; Steenfelt et al., 2005). The TTG gneisses contain numerous meter- to kilometer-scale conformable layers of multiply-deformed supracrustal rocks (predominantly amphibolites) and layered anorthositic complexes consisting of an anorthosite, leucogabbro, gabbro and ultramafic rock association, with minor sedimentary rocks (Figs. 2, 3) (see Bridgwater et al., 1976; Myers, 1976, 1985; Garde, 1997, 2003; Windley and Garde, 2009; Nutman et al., 2007a; Windley, 1969). Contacts between the TTG gneisses and the supracrustal belts and anorthosite complexes are typically marked by 5 to 20 meter wide shear zones (Fig. 4). Trains of 1 to 200 meters wide, 1 to 1000 meters long concordant, parallel to the dominant foliation, lenses of amphibolite within the orthogneisses can be traced for several kilometers

(Figs. 2, 3). These amphibolite lenses are likely to be relicts of earlier continuous layers that were sheared, folded and redistributed by deformation. The thicknesses of supracrustal associations and layered anorthositic complexes in some places reach up to 2 kilometers (Windley and Garde, 2009). These rock types occur in alternating granulite and amphibolite facies belts or zones (Bridgwater et al., 1976; Garde, 1990; Windley and Garde, 2009). Greenschist facies supracrustal rocks are restricted to the Mesoarchean Tartoq Group (Windley and Garde, 2009; Kisters et al., 2012; Szilas et al., 2013a).

The protoliths of the TTG gneisses were emplaced into the supracrustal rocks and spatially associated anorthositic complexes (Wells, 1979, 1981, Nutman and Garde, 1989; Myers, 1985; Windley and Garde, 2009; Polat et al., 2010; Hoffmann et al., 2012). The emplacement of the TTGs took place mainly along thrust faults and was accompanied by recumbent isoclinal folding (Myers, 1985; Hanmer et al., 2002; Hanmer and Greene, 2002; Garde, 1997, 2007; Windley and Garde, 2009; Polat et al., 2010), resulting in significant crustal thickening. The TTG gneisses also underwent extensive migmatization during a series of tectonothermal events (Friend and Nutman, 2005a; Nutman et al., 2013; Hoffmann et al., 2011). The ca. 2550 Ma Qôrqut granites were interpreted to have been derived from partial melting of Eoarchean and Mesoarchean orthogneisses (Moorbath et al., 1981; Nutman and Friend, 2007). Recently, Næraa et al. (2014) suggested that the Qôrqut granites were derived from Eoarchean mafic crust during late- to post-accretion tectonic processes.

The petrogenetic origin of the TTGs has been attributed to diverse processes, including melting of the sub-arc mantle wedge, subducted slabs and amphibolites in thickened arcs (Nutman et al., 1996, 1999, 2004, 2013; Steenfelt et al., 2005; Garde, 2007; Tappe et al., 2011; Kolb et al., 2012; Nagel et al., 2012; Szilas et al., 2012a; Hoffmann et al., 2011, 2014). Windley

and Garde (2009) suggested that the TTGs were generated in mature island arcs and Andean-type continental margins. Nutman et al. (2013) proposed that the protoliths of the Eoarchean Itsaq Gneiss Complex were derived mainly from eclogitic mafic crustal rocks with subduction geochemical characteristics.

Early generations of structures (e.g., D₁) have been intensely overprinted and transposed by the later structures (e.g., D₂ – D₅; see Hall and Friend, 1979; Friend et al., 1988; Chadwick, 1990; Crowley, 2002; Kolb et al., 2012), resulting in complex fold and shear zone patterns. Similarly, Eoarchean to Mesoarchean magmatic and metamorphic rocks were overprinted by the Neoarchean tectonothermal events (e.g., Kalsbeek and Pidgeon, 1980; McGregor and Friend, 1992; Nutman et al., 1989, 1996; Nutman and Friend, 2007; Friend and Nutman, 2005a; Dziggel et al., 2014; Keulen et al., 2014).

Field and geochronological studies indicate that the Archean craton of West Greenland was built by a series of collision events (Friend and Nutman, 1991, 2005a; Friend et al., 1988, 1996; Nutman et al., 2004), and its formation can be best explained by horizontal tectonics that involved accretion of island arcs and continental blocks (Bridgwater et al., 1976; Friend et al., 1988, 1996; McGregor et al., 1991; Nutman and Collerson, 1991; Crowley, 2002; Friend and Nutman, 2001, 2005a; Windley and Garde, 2009). Bridgwater and co-workers (1974) were among the first geologists to recognize the role of horizontal tectonics in the formation of poly-phase fold and thrust structures, intrusion of multiple, syntectonic TTG plutons, and generation of amphibolite to granulite facies metamorphic rocks. Later studies provided additional field evidence for horizontal tectonics (Nutman and Collerson, 1991; Friend et al., 1988; Nutman et al., 1989, 2002; Kisters et al., 2012; Nutman et al., 2013, 2015a, 2015b). Studies in the Isua

region suggest that horizontal tectonic processes began as early as 3690 Ma (Hanmer et al., 2002; Hanmer and Greene, 2002; Nutman and Friend, 2009; Nutman et al., 2009, 2015a).

3. Tectonic models for the Archean craton of West Greenland

Two major tectonic models have been proposed to explain the geologic history of the Archean craton of West Greenland: (1) terrane accretion model; and (2) arc crustal block accretion model. The main features of the models are summarized below.

3.1. Terrane accretion model(s)

On the basis of extensive field and zircon U-Pb geochronological data, Friend and co-workers (Friend et al., 1987, 1988, 1996; Friend and Nutman, 2001, 2005; Nutman et al., 2007b) developed a terrane accretion, *sensu lato*, model to explain the geology of fault-bounded crustal domains, with distinct metamorphic, structural, and isotopic histories. The terrane model was first applied to the Godthåbsfjord (Nuuk) region by Friend et al. (1987). The model has been refined and extended to other regions of West Greenland, as new geochronological, field and geochemical data have been amassed over the last twenty-five years (Friend and Nutman 2005a; Nutman and Friend, 2007, 2009; Garde, 2007; Polat et al., 2007, 2008, 2009b; Nutman et al., 2004, 2009). The revised model includes, from north to south, the following terranes: the Eoarchean Aasivik terrane, the Eoarchean Qarlit Tasersuat assemblage (terrane?), the Mesoarchean to Neoarchean Akia terrane, the Eoarchean Isukasia terrane, the Mesoarchean Kapisilik terrane, the Eoarchean Færinghavn terrane, and the Mesoarchean to Neoarchean Tre Brødre, Tasiusarsuaq, Sioraq, Paamiut, Neria, and Sermiligaarsuk terranes (Fig. 1; see Rosing et al., 2001; Nutman et al., 2004; Friend and Nutman, 2001, 2005a; Nutman and Friend, 2007, and

references therein). The Eoarchean Aasivik and Qarlit Tasersuat terranes occur within Mesoarchean to Neoarchean rocks. The Neria terrane is interpreted as a refolded nappe (see Windley and Garde, 2009). All terranes are composed mainly of juvenile rocks and were assembled through several collision events in the late Archean (Nutman et al., 2004, 2007b; Friend and Nutman, 2005a, 2005b; Steenfelt et al., 2005; Polat et al., 2008, 2010; Hoffmann et al., 2012; Szilas et al., 2013a). These terranes underwent poly-phase, high-strain heterogeneous deformation and multiple episodes of metamorphism resulting from several tectonothermal events (Friend and Nutman, 2001). Although these tectonic terranes have distinct sequences of structural, metamorphic, and magmatic events (Friend and Nutman, 2005a), they have broadly similar rock types, and styles of deformation, magmatism and metamorphism (Windley and Garde, 2009). However, the order and subduction polarity of collisions between different terranes have not been well established.

Some terranes, such as the Eoarchean Isukasia terrane, are composite terranes, including several tectonically juxtaposed lithotectonic fragments (Nutman et al., 2015a). The Akia terrane also contains two, 3220 Ma and 3071-2990 Ma, crustal blocks (Garde, 1997, 2007).

The terrane boundaries are marked by up to 200 meter wide mylonitized, amphibolite facies volcanic and sedimentary rocks and serpentinites. Nutman and Friend (2007) proposed that these mylonitized rocks are deeper crustal equivalents of parautochthonous cover sequences and allochthonous ophiolitic/accretionary assemblage nappes occurring in Phanerozoic orogens. The mylonitized accretionary prisms between various tectonic blocks are interpreted to mark the closure of Archean ocean basins by horizontal tectonics. In the context of plate tectonics, the terranes and terrane boundaries can be defined as “tectonic blocks” and “suture zones”, respectively. Field observations indicate that most rocks in these terranes underwent an early

phase of isoclinal folding, followed by a second generation of isoclinal recumbent nappe formation (Berthelsen and Henriksen, 1975, Friend et al., 1988, 1996; Windley and Garde, 2009). Thrust faults between different terranes were folded during the late Archean accretion events at 2710-2720 Ma and 2650–2600 Ma (Friend et al., 1988; Nutman and Friend, 2007). Terrane accretion was followed by regional recumbent isoclinal folding and superimposed upright folding (Nutman and Friend, 2007). Collisions between the terranes were also accompanied by magmatism and metamorphism (Fiend et al., 1988; Windley and Garde, 2009; Dziggel et al., 2014). Folding, shearing and metamorphic recrystallization obliterated most, if not all, kinematic indicators in the mylonitized terrane boundaries (Friend and Nutman, 2001), making it difficult to determine subduction polarity.

3.2. Arc crustal accretion model

The arc crustal accretion model for the Archean craton of West Greenland has been proposed by Windley and Garde (2009). In this model the craton is divided into six fault-bounded tectonic blocks that display similar geological cross sections. These blocks, from north to south, consists of the Maniitsoq, Fiskefjord, Sermilik, Bjørnesund, Kvanefjord, and Ivittuut blocks. In this model each block consists of southerly upper and northerly lower zones. The upper zones are characterized by prograde amphibolite facies metamorphism, whereas the lower zones display granulite facies metamorphism; some parts of these zones are partly to completely retrogressed to amphibolite facies. According to Windley and Garde (2009), the tectonic blocks are remnants of Archean island arcs and Andean-type continental margins. The Godthåbsfjord region, where the Færinghavn, Tre Brødre, Kapisilik and Isukasia terranes of Friend and Nutman

(2005a) are located, is defined as the Godthåbsfjord-Ameralik belt. The boundaries between some crustal blocks overlap with the terrane boundaries.

It is suggested that the style of deformation changes downward within crustal blocks in that upper zones were mostly deformed by one major phase of isoclinal folding, and lower zones underwent two to three phases of kilometer-scale folding, resulting in complex fold interference patterns. In all blocks TTG protoliths have extensively intruded supracrustal rocks and associated layered anorthositic complexes mainly along shear zones. Because of intense deformation and extensive TTG intrusion, the supracrustal rocks and anorthosite, gabbro, leucogabbro and ultramafic rock layers are preserved mainly as trains of lenses or folded lenses (Windley and Garde, 2009). These blocks were thickened by a combination of thrusting, isoclinal folding and TTG intrusion. Given that the terrane terminology has been embedded in the literature for over twenty-five years, we will continue to use this terminology.

Although the terrane and arc crustal accretion models have different names for the same tectonic assemblages, the tectonic processes and crust-building events proposed by the two models to explain the evolution of the Archean craton in West Greenland are broadly similar, involving lateral accretion of juvenile igneous rocks. Both models suggest that Archean crustal growth in West Greenland is a product of prolonged, complex tectonothermal events and comparable to those of Phanerozoic orogenic belts.

4. Supracrustal belts, layered anorthositic and ultramafic rocks

Supracrustal belts (or greenstone belts) are the lithotectonic assemblages of metamorphosed volcanic and sedimentary rocks, containing variable proportions of ultramafic to mafic intrusive rocks. The majority of supracrustal belts in the Archean craton of West

Greenland underwent amphibolite or granulite facies metamorphism (Windley and Garde, 2009). The Mesoarchean (3000 Ma) Tartoq supracrustal belt is the only one that preserves greenschist facies metamorphism (Kisters et al., 2012; Szilas et al., 2013a, and references therein).

The Mesoarchean supracrustal rocks in West Greenland are often temporally and spatially associated with an assemblage of layered anorthositic complexes (Windley and Smith, 1974, 1976; Myers, 1985; Dymek and Owens, 2001; Polat et al., 2008; 2009a, 2011a, 2011b; Hoffmann et al., 2012). Despite multiple phases of deformation and amphibolite to granulite facies metamorphism, pillow structures, cumulate textures and igneous layering are locally well preserved in many supracrustal belts and anorthositic complexes.

In the following sections, we review the major geological characteristics of these belts and layered complexes. Emphasis are placed on the Isua, Ivisaartoq-Ujarassuit, Storø, Fiskenæsset, Bjørnesund, Ravns Storø and Tartoq supracrustal belts, and the Fiskenæsset anorthosite complex (Fig. 1) that have been studied by the senior author (see Polat et al., 2011a, 2012). In addition, we summarize the main geological features of the Qussuk-Bjørneøen and Grædefjord supracrustal belts, layered ultramafic rocks in the Isukasia terrane, and the Naajat Kuuat anorthosite complex (Fig. 1).

4.1. Supracrustal belts

4.1.1. The Eoarchean Isua supracrustal belt

The Isua supracrustal belt is the largest Eoarchean volcanic and sedimentary rock assemblage in West Greenland (Keto and Kurki, 1967; Allaart, 1976; Bridgwater et al., 1976; Nutman, 1986; Nutman et al., 1997, 2009, 2013; Appel et al., 1998; Myers, 2001; Nutman and Friend, 2009). It is exposed within the Itsaq Gneiss Complex in the composite Isukasia terrane

(Nutman et al., 1997, 2009, 2013). Geochronological and isotopic studies indicate that the belt contains rocks ranging in age from 3800 to 3700 Ma (Moorbath et al., 1973; Baadsgaard et al., 1986; Kamber et al., 1998; Nutman et al., 1997, 2002, 2009; Frei et al., 2004; Nutman and Friend, 2009; Hoffmann et al., 2010). On the basis of field relationships and geochronological data, Nutman and co-workers (Nutman and Friend, 2009; Nutman et al., 2009; Nutman et al., 2015a) showed that the belt and bordering orthogneisses belong to two tectonically-juxtaposed sub-terrane: a ca. 3800 Ma southern sub-terrane and a ca. 3700 Ma northern sub-terrane. These sub-terrane appear to have been juxtaposed between 3680 and 3660 Ma. The boundary between these two sub-terrane is characterized by strongly mylonitized sedimentary rocks consisting of carbonate, chert, and banded iron formation (BIF). Both the northern and southern sub-terrane are composed of similar lithologies including mafic to ultramafic volcanic rocks, ultramafic layers, chert, and BIF (Nutman et al., 2009; Appel et al., 1998; Myers, 2001; Friend et al., 2008; Nutman and Friend, 2009; Nutman et al., 2009, 2015a).

The Isua supracrustal belt has undergone several phases of deformation and amphibolite facies metamorphism (Nutman et al., 1984; Myers, 2001; Nutman et al., 2002, 2007b; Hanmer et al., 2002; Nutman and Friend, 2009). Although the belt underwent poly-phase deformation and amphibolite facies metamorphism, low-strain zones contain primary volcanic and sedimentary structures, including pillow structures, pillow breccia and conglomerates (Fig. 5) (Appel et al., 1998, 2009, Komiya et al., 1999; Fedo, 2000; Myers, 2001; Polat et al., 2002; Friend et al., 2008; Furnes et al., 2007; de Wit et al., 2013). The style of deformation (e.g., thrust faults, asymmetric and overturned folds) and the nature of lithologies (e.g., pillow basalts, cherts, serpentinitized peridotites) in the Isua belt are similar to those in Phanerozoic suture zones (Figs. 5, 6).

The ca. 3800 Ma sub-terrane contains a suite of picrites to basalts with a transitional to tholeiitic affinity, and “enriched” basalts with a calc-alkaline affinity (Polat and Hofmann, 2003; Jenner et al., 2009). The ca. 3700 Ma sub-terrane consists of an association of picrites to basalts with a calc-alkaline to transitional affinity; and a suite of boninites with a tholeiitic affinity (Polat et al., 2002, 2011a, Polat and Hofmann, 2003; Appel et al., 2009; Hoffmann et al., 2010). The trace element systematics of volcanic rocks in both sub-terrane are consistent with subduction zone geochemical signatures, suggesting that they originated in a forearc or possibly in a juvenile oceanic island arc tectonic setting (Polat and Hofmann, 2003; Jenner et al., 2009; Furnes et al., 2007, 2009; Hoffmann et al., 2010).

On the basis of field relationships, geochemistry and geochronology, Nutman et al. (2015a) showed that the rocks in the northern sub-terrane are characterized by tectonic imbrication and display a temporal shift from mafic, through intermediate, to felsic composition, consistent with the formation of the sub-terrane in an intra-oceanic island arc, called “proto-arc”. They also attributed the intrusion of the imbricated supracrustal rocks by the 3700-3690 Ma calc-alkaline tonalities to the maturation of the “proto-arc”, resulting from partial melting of eclogitized mafic crust at the base of the tectonically thickened arc (cf., Hoffmann et al., 2011). In contrast, Polat and Frei (2005) argued that ridge subduction played an important role in the partial melting of the imbricated arc crust to produce TTGs.

4.1.2. The Mesoarchean (ca. 3075 Ma) Ivisaartoq-Ujarassuit supracrustal belt

The Mesoarchean (ca. 3075 Ma) volcanic and sedimentary rocks exposed in the Ivisaartoq and Ujarassuit areas in the upper Godthåbsfjord (Nuuk) region are part of the same lithotectonic assemblage (Fig. 1) (Hall and Friend, 1979; Chadwick, 1990; Friend and Nutman, 2005a; Polat

et al., 2007, 2008; Ordóñez-Calderón et al., 2009; Nutman et al., 2015b).

The Ivisaartoq-Ujarassuit belt is the largest Mesoarchean supracrustal lithotectonic assemblage in the Godthåbsfjord region (Fig. 1). The belt occurs within the Mesoarchean (3075-2950 Ma) Kapisilik terrane (Friend and Nutman, 2005a), which is tectonically bounded by the Eoarchean (3870-3600 Ma) Isukasia terrane to the north, and by the Eoarchean Færingehavn and the Neoarchean Tre Brødre terranes to the south and west, respectively (see Friend and Nutman, 2005a; Polat et al., 2007). Nutman et al. (2015b) have recognized a Mesoarchean tectonic klippe of dismembered mafic to ultramafic rocks, formerly belonging to the Ivisaartoq-Ujarassuit supracrustal belt, in the southern part of the Isukasia terrane, suggesting that the Kapisilik terrane was tectonically emplaced over the Isukasia terrane at about 2970 Ma.

The primary igneous structures, including pillow basalts, pillow breccia and magmatic layering, are better preserved in the Ivisaartoq area than the Ujarassuit counterpart (Chadwick, 1990; Polat et al., 2007, 2008; Ordóñez-Calderón et al., 2009).

The Ivisaartoq section of the supracrustal belt is composed predominantly of pillow basalts, picrites, gabbros and serpentinized peridotites, with minor diorites and siliceous, pyrite-bearing volcanoclastic rocks (Fig. 7) (Hall and Friend, 1979; Hall, 1980; Chadwick, 1985, 1990; Polat et al., 2007, 2008, 2009a). The pillow basalts are characterized by a tholeiitic affinity and display well-preserved core and rim structures (Hall, 1980; Chadwick, 1990; Polat et al., 2007, 2008, 2009a). Calc-silicate metasomatic alteration, consisting mainly of an assemblage of epidote, quartz, hornblende, diopside, calcite and garnet, is widespread in the pillow basalts, gabbros and diorites (Fig. 7a, b) (Polat et al., 2007; Ordóñez-Calderón et al., 2009). Peridotites are exposed discontinuously as three major layers throughout the sequence (Fig. 7d) (Chadwick, 1985, 1990). In several locations the gabbros contain up to 15 centimetres long anorthosite

xenoliths (Polat et al., 2008). Sedimentary rocks are composed of quartzitic gneisses, biotite schists, and cherts (Chadwick, 1985, 1990; Ordóñez-Calderón et al., 2009). The siliceous volcaniclastic rocks yielded a zircon U-Pb age of 3075 ± 15 Ma (Friend and Nutman, 2005a; Polat et al., 2007).

Migmatites occur at the contact between the Isukasia and Kapisilik terrane (Fig. 7e), suggesting that amphibolites were partially melted during tectonic juxtaposition of these terranes at about 2970 Ma. The tectonic collision between the two terranes produced asymmetric folds and refolded thrust structures in the Ujarassuit area (Fig. 7f). The Ujarassuit part of the belt is dominated by basaltic amphibolites, with rare pillow structures (Ordóñez-Calderón et al., 2009). In addition, basaltic andesites, andesites, boninites, peridotites, and volcaniclastic rocks are exposed in the Ujarassuit area (Ordóñez-Calderón et al., 2009).

The presence of abundant pillow basalts, evidence for extensive high-temperature seafloor hydrothermal alteration (epidosites), and subduction zone geochemical characteristics of the basalts, boninites, picrites, andesites, basaltic andesites, gabbros, anorthosites, and diorites in the Ivisaartoq-Ujarassuit supracrustal are collectively consistent with the formation of the belt as a Mesoarchean subduction-related ophiolite (see Polat et al., 2007, 2008; Ordóñez-Calderón et al., 2009; Dilek and Polat, 2008; Furnes et al., 2015).

4.1.3. The Mesoarchean (ca. 3080 Ma) Qussuk-Bjørneøen supracrustal belt

The Mesoarchean Qussuk-Bjørneøen supracrustal belt (Fig. 1) is located at the eastern edge of the Akia terrane, or the Fiskefjord crustal block of Windley and Garde (2009), in the Godthåbsfjord region (Garde 1997, 2007; Garde et al., 2012). The belt includes numerous slices of intensely deformed volcanic, volcaniclastic, and intrusive rocks, including tholeiitic basalts,

andesites, gabbros, and orthopyroxene-rich ultramafic cumulates (Garde, 2007). Relict pillow structures are preserved at Bjørneøen. Volcaniclastic rocks in the central Bjørneøen and near the head of Qussuk have a zircon U-Pb age of 3071 Ma (Garde et al., 2007, 2012). The belt was intruded by voluminous TTGs at ca. 3000 Ma. Although main contacts between the supracrustal rocks and the TTG gneiss are tectonic or tectonized, intrusive relationships are well documented in many outcrops (Garde, 2007). The supracrustal rocks and the TTG gneisses were intruded by syntectonic granites at 3005-2980 Ma and metamorphosed at amphibolite facies conditions between 2990 and 2970 Ma. The Qussuk-Bjørneøen belt shares the lithological and geochronological features of the ca. 3075 Ma Ivisaartoq-Ujarassuit belt (see Polat et al., 2008; Ordóñez-Calderón et al., 2009). The geochemical characteristics of the Qussuk-Bjørneøen supracrustal rocks are consistent with an oceanic island arc setting (Garde, 2007).

4.1.4. The Mesoarchean to Neoarchean Storø supracrustal belt

The Storø supracrustal belt (Fig. 1) is in a structural contact between two terranes; the Eoarchean Færingehavn terrane to the east, and the Mesoarchean Akia terrane to the west (Friend and Nutman, 2005a; Hollis, 2005, Nutman et al., 2007b; Nutman and Friend, 2007; van Gool et al., 2007). The belt is characterized by tectonically imbricated Mesoarchean (3060 Ma) and Neoarchean (ca. 2800 Ma) amphibolite facies igneous and sedimentary rocks, consisting of basalts (amphibolites), anorthosite-leucogabbro-gabbro association, garnet-biotite gneisses, quartzitic gneisses, and ultramafic rocks (Fig. 8) (Hollis et al., 2004; Knudsen et al., 2007; Østergaard and van Gool, 2007; van Gool et al., 2007; Ordóñez-Calderón et al., 2011; Scherstén et al., 2012; Szilas and Garde, 2013; Szilas et al., 2014). Sedimentary rocks locally underwent migmatization (Fig. 8e). Contacts between the Mesoarchean and Neoarchean supracrustal rocks

and the neighboring Eoarchean to Neoarchean TTG gneisses are typically marked by mylonites. Based on their field characteristics and locations in the tectonostratigraphy, amphibolites are divided into lower (homogeneous) and upper (banded) units (van Gool et al., 2007; Ordóñez-Calderón et al., 2011). The lower amphibolites are intruded by the anorthosite-leucogabbro-gabbro association that is in turn intruded by a ca. 3050 Ma tonalite sheet. Polyphase deformation (Fig. 8b) and amphibolite facies metamorphism during terrane accretion between ca. 2650 and 2600 Ma have obliterated most of primary textural and mineralogical characteristics of the igneous and sedimentary rocks. The geochemical characteristics of the Storø amphibolites are consistent with a subduction zone geodynamic setting and partial melting of a shallow (< 80 km) mantle source (Ordóñez-Calderón et al., 2011).

4.1.5. The Mesoarchean Grædefjord supracrustal belt

The Grædefjord supracrustal belt (Fig. 1) is located to the south of Grædefjord in the Tasiusarsuaq terrane, at the contact between the Bjørnesund and Sermilik blocks in Windley and Garde (2009). The belt is dominated by strongly deformed mafic, ultramafic, and andesitic amphibolites, and intruded by the 2950-2880 Ma TTGs (Kalsbeek and Pidgeon, 1980; Pidgeon and Kalsbeek, 1978; Szilas et al., 2013b). Both the supracrustal rocks and TTGs were metamorphosed under amphibolite to lower granulite facies conditions (Pidgeon and Kalsbeek, 1978; McGregor and Friend, 1992; Nutman and Friend, 2007; Riciputi et al., 1990; Schumacher et al., 2011). Szilas et al. (2013b) interpreted the Grædefjord supracrustal rocks having formed in a subduction zone setting. Our unpublished geochemical data from this belt support this interpretation.

4.1.6. *Mesoarchean supracrustal rocks in the Fiskenæsset region*

Supracrustal rocks associated with the Fiskenæsset anorthosite complex are characterized by both layered and massive amphibolites (Myers, 1985; Weaver et al., 1981, 1982; Polat et al., 2009b). Mineralogically, the amphibolites are composed of hornblende and plagioclase, with minor pyroxene, epidote, quartz, and garnet (Fig. 9a-c) (Polat et al., 2009b). The protoliths of the TTG gneisses were emplaced as sub-concordant layers between the stratigraphic units of the Fiskenæsset anorthosite complex and the associated amphibolites mainly along thrust faults. On a meter to kilometer scale, the TTG gneisses separate the amphibolites and the units of the anorthosite complex into thin layers and trains of lenses. Despite intense deformation, intrusive relationships between the TTG gneisses and amphibolites are locally preserved in the Majorqap qâva and Sinarssuk areas. Because of several phases of ductile deformation and extensive shearing, pillow structures in the Fiskenæsset amphibolites are preserved only in several outcrops (Escher and Myers, 1975; Polat et al., 2009b). The anorthosite complex, supracrustal rocks and TTG gneisses were affected by granulite facies metamorphism and retrogressed under upper-amphibolite facies conditions (Myers, 1985; McGregor and Friend, 1992; Schumacher et al., 2011).

The majority of amphibolite layers in the Fiskenæsset region have subduction zone geochemical signatures. Four amphibolite samples from Bjørnesund and Nunatak have a high-magnesian andesitic composition, providing additional evidence for subduction zone geodynamic processes (Polat et al., 2009b). Samples from several locations display N-MORB-like trace element patterns (Weaver et al., 1981, 1982; Polat et al., 2009b). The Fiskenæsset anorthosite complex and the associated amphibolites are inferred as relicts of Mesoarchean supra-subduction zone oceanic crust (Polat et al., 2009b, 2010, 2011a, 2011b, 2012).

4.1.7. The Mesoarchean Bjørnesund and Ravns Storø supracrustal belts

The Bjørnesund and Ravns Storø (also known as Ikkattup Nunaa) supracrustal belts (Fig. 1) are located to the south of the Fiskenæsset Complex in the Tasiusarsuaq terrane (Andersen and Friend, 1973; Andersen, 1974; Windley and Garde, 2009; Szilas et al., 2012a; Keulen et al., 2014). These belts are composed of similar rock types and were affected by similar deformation, magmatic and metamorphic events, suggesting that they were part of an originally continuous Mesoarchean supracrustal belt (Windley, 1968; Friend, 1975; Anderson, 1974; Windley and Garde, 2009; Szilas et al., 2012a; Keulen et al., 2014). The belts underwent mid to upper amphibolite facies metamorphism, three phases of folding, thrusting and strike-slip deformation (Fiend, 1975; Keulen et al., 2014). The Ravns Storø belt contains ca. 2908 Ma biotite \pm garnet quartzo-feldspathic gneisses of a probable sedimentary or a volcanoclastic origin (Andersen and Friend, 1973; Nutman et al., 2004).

Supracrustal rocks in the southern part of the Ravns Storø belt are intruded by the 2878 ± 10 Ma tonalities (Friend and Nutman, 2001). Keulen et al. (2014) showed that the Bjørnesund and Ravns Storø are intruded by the 2970 Ma Fiskenæsset anorthosite complex, 2920 Ma diorite and 2910-2880 Ma granodiorite. Szilas et al. (2012a) reported a ca. 2900 Ma zircon U-Pb age for fine-grained TTG sheets that intrude both belts. Amphibolites from these belts yielded 3020 ± 78 Ma and 2990 ± 41 Ma Sm-Nd and Lu-Hf regression (errorchron) ages, respectively (Szilas et al., 2012a). These ages suggest that the Bjørnesund and Ravns Storø belts formed at ca. 3000 Ma.

On the island of Ikkattup Nunaa, amphibolites, ultramafic schists (serpentinites, actinolite schists), mafic to felsic tuffs, pyroclastic rocks (e.g., lapilli tuffs, and ignimbrites), garnet-mica schists, deformed pillow basalts, and gabbros are the major rock types (Fig. 9d-e). In addition to these rocks, there are garnet amphibolites, quartz-feldspar-mica schists, and mafic to felsic dykes

in the belt. Contacts between different rock types, except for dikes, are predominantly structural, including asymmetric folds, S-C planar fabrics, and quartz veins. Outcrops of deformed pillow structures were observed only in a few localities (Fig. 9e). These pillows are strongly deformed and contain epidote-rich calc-silicate metasomatic mineral assemblages. Carbonate and silica alteration occur mainly along foliation planes in the amphibolites.

Rock types at Bjørnesund are similar to those on Ikkattup Nunaa, consisting predominantly of gabbros, amphibolites, deformed pillow basalts, and serpentinites (Fig. 9f). Similarly, contacts between different lithologies are marked by deformation, quartz veins, and carbonate and silica alteration. Contacts between gneisses and greenstone belts are generally characterized by strong deformation (folding and shearing), but intrusive relationships have also been observed.

The trace element systematics of the volcanic rocks in the Bjørnesund and Ravns Storø supracrustal belts are consistent with an oceanic island arc geodynamic setting (Cengija, 2010; Szilas et al., 2012a). Neodymium and Hf isotope systematics indicate a depleted mantle source for the amphibolites, suggesting that their protoliths were derived from a subarc mantle source.

4.1.8. The Mesoarchean (ca.3000 Ma) Tartoq supracrustal belt

The Tartoq supracrustal belt, also known as the Tartoq Group, is exposed in four areas, namely the Nuuluk, Iterlak, Amitsuarsua, and Bikuben (Fig. 1) (Kisters et al., 2012; Szilas et al., 2013a). The belt is located in the Kvanefjord block of Windley and Garde (2009). Like other Archean supracrustal belts, the Tartoq belt is composed of basaltic, gabbroic, ultramafic, and sedimentary rocks (Fig. 10) (Higgins, 1968, 1990; Appel and Secher, 1984; Petersen, 1992; Evans and King, 1993; Nutman and Kalsbeek, 1994; Nutman et al., 2004; Kisters et al., 2012; Szilas et al., 2013a, 2014). The belt underwent at least four phases of deformation and

heterogeneous metamorphism ranging from greenschist to lower granulite facies (Kisters et al., 2012). Contacts between different rock units are mainly structural and often marked by felsic mylonites (Fig. 10d, e). These contacts often display multiple phases of folding, shearing, carbonate and silica alteration, mylonitization, and transposition of the fabrics (Fig. 10f) (Polat and Dziggel, 2011). Due to intense shearing, carbonate and silica alteration, and several generations of folding, pillow structures in mafic volcanic rocks have largely been destroyed and preserved only in several locations (Fig. 10a). Ultramafic rocks, mostly serpentinites, are also strongly deformed and metamorphosed. The serpentinites are interpreted as lower arc cumulates (Szilas et al., 2014). The belt has been intruded by the 2950-2990 Ma TTGs (Nutman and Kalsbeek, 1994; Kisters et al., 2012). Some TTG sheets are tectonically imbricated with the volcanic rocks in the belt (Kisters et al., 2012; Szilas et al., 2013a).

Extensive geochemical data reported by Szilas et al. (2013a, 2014) indicate that the Tartog belt formed in a Mesoarchean supra-subduction tectonic setting. On the basis of field characteristics and geochemical data, Szilas and co-workers (2013a, 2014) interpreted the belt as a dismembered supra-subduction ophiolite in a subduction-accretion complex. The TTGs were derived mainly from partial melting of amphibolites in the subduction-accretion complex (Kisters et al., 2012).

4.2. Layered ultramafic intrusions and anorthositic complexes

4.2.1. Layered ultramafic rocks in the Isukasia terrane

Tectonically intercalated slices of layered ultramafic–mafic rocks, including chromite-bearing dunite, harzburgite, gabbro and minor anorthosite, occur within the Itsaq Gneiss Complex of the Isukasia terrane (Friend et al., 2002; Lowry et al., 2003). Friend et al. (2002)

interpreted these ultramafic rocks as fragments of >3800 Ma abyssal peridotites dismembered within an Eoarchean accretionary prism (Nutman et al., 1996; Friend et al., 2002).

4.2.2. Layered anorthositic complexes

The Archean craton of West Greenland contains the best-preserved, layered anorthositic complexes in the world (Myers, 1985; Ashwal, 1993; Owens and Dymek, 1997; Dymek and Owens, 2001; Windley and Garde, 2009; Polat et al., 2010, 2011a, 2011b; Hoffmann et al., 2012). These complexes consist mainly of anorthosite, leucogabbro, gabbro and ultramafic rocks (Fig. 1) (Windley and Smith, 1974; Myers, 1985; Polat et al., 2009b, 2011a). The anorthositic complexes consist of numerous conformable folded layers and lenses in the TTG gneisses of the Tasiarsuaq, Tre Brødre, Akia terranes and are typically associated with amphibolites (Windley and Garde, 2009). A few slices of anorthosites are also found in the Mesoarchean Kapisilit terranes (Friend and Nutman, 2005a). The TTG gneisses, amphibolites and anorthosite complexes underwent polyphase deformation and amphibolite to granulite facies metamorphism (Myers, 1985; Windley and Garde, 2009). They were deformed by an early phase of isoclinal folding that was followed by isoclinal recumbent nappe formation, giving rise to kilometer-scale fold interference patterns (Myers, 1985; Windley and Garde, 2009). The protoliths of the TTG gneiss intruded the anorthosite complexes along shear zones and dispersed them as trains of inclusions (Fig. 4e, f) (Myers, 1976; 1985; Windley and Garde, 2009). Figure 11 shows a tonalite sheet that was emplaced along a thrust fault zone between two slices of anorthosite-leucogabbro at Sinarssuk in the Fiskenæsset Complex. The best examples of anorthosite complexes in West Greenland occur in the Fiskenæsset, Fiskefjorden, Nordland and Kapisilit regions (Myers, 1985;

Owens and Dymek, 1997; Dymek and Owens, 2001; Windley and Garde, 2009; Polat et al., 2009b, 2010; Hoffmann et al., 2012). We focus on the Fiskenæsset anorthosite complex.

The Fiskenæsset Complex represents the largest and the most complete anorthositic complex in West Greenland (Windley and Smith, 1976; Myers, 1985; Windley and Garde, 2009; Polat et al., 2009b, 2010, 2011b, 2012). Although the complex underwent multiple phases of ductile deformation and high-grade metamorphism, the original field relationships, and primary igneous structures and textures are well preserved in numerous outcrops (Fig. 12) (Windley and Smith, 1974; Myers, 1985; Polat et al., 2009b, 2010; 2011b). Igneous layering in the complex consists of variable proportions of dunite, hornblende peridotite, hornblende pyroxenite, hornblendite, gabbro, leucogabbro and anorthosite (Myers, 1985; Polat et al., 2009b, 2011b; Polat, 2014). Field and petrographic studies indicate that the Fiskenæsset Complex was emplaced into Mesoarchean oceanic crust as multiple sills and dykes of magma and crystal mush, forming an association of *ca.* 550 m-thick anorthosite, leucogabbro, gabbro and ultramafic layers (Myers, 1985; Polat et al., 2009b; 2010, 2011b).

Zircon U-Pb dating of anorthosite and leucogabbro samples from the Majorqap qâva section has yielded an age of 2936 ± 13 Ma for the complex (Souders et al., 2013). A hornblendite dyke at Majorqap qâva produced zircon U-Pb ages between 2950 to 2700 Ma (Keulen et al., 2010). Whole-rock samples of the anorthosite, leucogabbro, gabbro and ultramafic rocks on the Island of Qeqertarsuatsiaq yielded 2973 ± 28 Ma (MSWD=33) Sm-Nd and 2945 ± 36 Ma (MSWD=44) Pb-Pb isotope regression ages (Polat et al., 2010). All these ages are collectively consistent with the emplacement of the Fiskenæsset Complex into Mesoarchean oceanic crust between 3000 and 2930 Ma (Escher and Myers, 1975; Myers, 1985; Polat et al., 2009b).

Field relationships, Nd isotopic characteristics ($\epsilon_{\text{Nd}}=+3.3$), mantle-like $\delta^{18}\text{O}$ values, and trace element systematics of mineral and whole-rock samples are collectively consistent with the generation of the Fiskenæsset Complex as juvenile oceanic island crust (Polat et al., 2009b, 2010, 2011b, 2012; Polat and Longstaffe, 2014; Huang et al., 2014). The presence of overturned igneous layers and regional scale recumbent folds, and thrust faults are collectively consistent with a convergent plate margin tectonic setting for the Fiskenæsset Complex (Figs. 11, 12a).

Field, lithological, and mineralogical characteristics of the ca. 3000 Ma Naajat Kuuat anorthosite complex are similar to those of the Fiskenæsset Complex (Hoffmann et al., 2012). The trace element and Hf-Nd isotope systematics of the Naajat Kuuat Complex suggest a juvenile island arc tectonic setting (Hoffmann et al., 2012). Amphibolites associated with the Naajat Kuuat Complex display N-MORB and oceanic island arc trace element signatures, as do the Fiskenæsset amphibolites (Polat et al., 2009b). The presence of igneous amphibole in both complexes is consistent with hydrous sub-arc mantle sources.

Owens and Dymek (1997) and Dymek and Owens (2001) studied the geochemical characteristics of the amphibolite facies Buksefjorden and granulite facies Nordland anorthosites in the Akia and Tre Brødre terranes, respectively, and also concluded that these anorthosites were derived from hydrous magmas.

5. Comparison of outcrop- and regional-scale structural patterns

Figure 13 shows a series of field photographs taken from a ca.1 kilometer long and 10 to 20 meters wide shear zone between the Akuliaq supracrustal belt and the bordering TTG gneisses in the Akuliaq Peninsula of the Paamiut region (Fig. 1; see also Fig. 4a-c) (GPS coordinates: N 62° 04' 25.6" and W 49° 04' 18.3"). For descriptive purposes this shear zone is

informally called “the Akuliaq shear zone”. The intensity of deformation along the shear zone is heterogeneous. The Akuliaq Peninsula is located in the Paamiut terrane of Friend and Nutman (2001) and in the Kvanefjord block of Windley and Garde (2009). Like other Archean supracrustal belts in the region, this supracrustal belt underwent at least three phases of deformation and amphibolite facies metamorphism (Glendenning, 2011; Hastie, 2011). Despite polyphase deformation and amphibolite facies metamorphism, the belt preserves relict pillow structures and intrusive relationships (Glendenning, 2011; Hastie, 2011).

The Akuliaq shear zone is a bifurcated shear zone and composed of two major rock types: (1) fine- to coarse-grained, strongly folded mylonitic tonalitic gneiss (40-80%); and (2) highly-sheared mylonitic amphibolite (20-40%) (Figs. 4a-c, 13). The fine-grained mylonitic tonalite is interpreted as syn-tectonic melt intruding along the shear zone that developed in mafic volcanic rocks (now amphibolite). Some parts of the Akuliaq shear zone resemble a small-scale tectonic *mélange* in which folded, sheared and transposed tonalitic rocks are dispersed in a sheared amphibolitic matrix (Fig. 13c-f). The Akuliaq shear zone contains isoclinal folds, refolded isoclinal folds, and sheath folds displaying fold interference patterns resulting from the superimposition of two and three generations of folds (Fig. 13). Truncation and transposition of these folds resulted in hook-, fork-, spoon-, lens-, and eye-shaped tonalitic mylonites floating in the amphibolitic matrix (Fig. 13c-f).

Figures 2 and 3 display regional-scale fold patterns in the Fiskefjord and Godthåbsfjord-Ameralik regions, respectively. A comparison of the geometries of the outcrop-scale fold patterns in the Akuliaq shear zone with those developed on regional scales reveal great similarities between the two scales. These similarities suggest that Archean terranes in West Greenland can be interpreted as collages of lithotectonic domains separated by heterogeneous

shear zones and that the protoliths of the TTG gneisses were emplaced along the major shear zones as syn-tectonic intrusions.

6. Field evidence for melting of amphibolites and formation of TTGs

A detailed discussion of the petrogenesis of Archean TTGs in West Greenland is beyond the scope and objective of this contribution. The origin of these rocks were recently discussed in several studies (see Steenfelt et al., 2005; Hiess et al., 2009, 2011; Nagel et al., 2012; Nutman et al., 2013; Huang et al., 2012; Hoffmann et al., 2011, 2014). The main objective of this section is to present field evidence for the formation of felsic rocks (TTG and granites) through partial melting of amphibolites in shear zones. Although the felsic rocks show a wide range of compositions, for the sake of simplicity, we use the term “TTG” as a field description for all intrusive felsic rocks discussed in this section. Field evidence presented here was obtained during reconnaissance studies by the first author in the Mesoarchean Kapisilit and Tasiusarsuaq terranes (Figs. 14, 15).

Amphibolites occur either as large supracrustal belts (e.g., the Isua, Ivisaartoq, Qussuk-Bjørneøen supracrustal belts), or as numerous, 1 to 200 meters wide lenses within the TTG gneisses (Polat et al., 2009b, 2011a). The latter type of amphibolites share the deformation and metamorphic characteristics of the surrounding TTG gneisses and are likely to be remnants of earlier continuous layers that were sheared, folded, transposed and redistributed by deformation.

Field observations and petrographic studies suggest that the amphibolites were derived predominantly from basaltic (pillowed) protoliths. Gabbroic precursors are also recognized in several locations. The trace element characteristics of the basaltic and gabbroic protoliths are consistent with a subduction zone setting, suggesting that they represent fragments of Archean

oceanic island arc crust (Garde, 2007; Polat et al., 2009b, 2009c, 2011a, 2011b; Szilas et al., 2012a, 2012b, 2013b).

As in many Archean migmatites (see Passchier et al., 1990; Sawyer, 2008), the amphibolites and TTGs in West Greenland display complex intrusive and structural relationships (Figs. 14, 15). Both the amphibolites and TTGs display heterogeneous deformation, ranging from slightly deformed to strongly mylonitized rocks (Chadwick, 1985; Crowley, 2003; Nutman et al., 2000, 2004; Friend and Nutman, 1991, 2005b). Lenses of deformed amphibolites occur as trails of conformable (parallel to the dominant foliation) inclusions around the folded gneisses (Figs. 2, 3). The presence of folded amphibolites that are cut by TTG veins in some outcrops indicate that the deformation and metamorphism of the basaltic protoliths had already taken place prior to the intrusion of these TTGs (Figs. 14, 15). The occurrence of several generations of cross-cutting TTG veins in some outcrops is attributed to multiple melting processes resulting from different tectonothermal events. In many outcrops, melting of the amphibolites appears to be coeval with isoclinal folding and shearing, whereas in other outcrops the amphibolites are cross cut by the TTG veins (Fig. 14a-c), reflecting several stages of melt formation and reworking of the amphibolites at various crustal depths (see Hoffmann et al., 2014). Where the amphibolites and gneisses are folded together, melts tend to concentrate in the fold hinges and along foliation planes (Fig. 15), indicating that these low-pressure areas acted as melt migration channels. Previous studies showed that the formation of Archean TTGs in West Greenland is closely associated with thrusting and isoclinal nappe forming events (Bridgwater et al., 1974; Friend et al., 1987, 1988, 1996; Myers, 1985; Nutman et al., 1993; Hanmer et al., 2002; Nutman and Friend, 2007; Windley and Garde, 2009; Kisters et al., 2012; Keulen et al., 2014), providing a genetic link between TTG formation and crustal thickening in response to tectonic collisions.

In summary, we suggest that the basaltic and gabbroic protoliths of the supracrustal belts (now amphibolites) originated in oceanic island arcs. Then they were buried down to lower crustal depths by folding and thrusting, metamorphosed to amphibolite to granulite facies, or possibly to eclogite facies, and then underwent partial melting to produce TTGs (see Hoffmann et al., 2011, 2014; Nutman et al., 2015a). We are not claiming that all TTGs and granites in the Archean craton of West Greenland were generated by partial melting of amphibolites in thickened arcs. As discussed above, it is likely that these TTGs were generated by a combination of melting processes including melting of amphibolites in thickened arcs, melting of subducting slabs or oceanic plateaus (see Martin et al., 2014), and melting of sub-arc mantle peridotites. Recent models favor melting of thickened crust rather than subducting slabs (Nagel et al., 2012; Hoffmann et al., 2014).

Given that we cannot quantify the volume of TTGs produced by different melting processes, the relative proportions of TTGs originating from the melting of amphibolites in thickened arcs versus slab, oceanic plateau and sub-arc mantle peridotite melting are currently unknown. In addition, field and geochronological studies reveal that melting of amphibolites occurred during multiple tectonothermal events (Nutman et al., 1993; Nutman et al., 2007b); thus, individual TTG sheets that formed in a particular tectonothermal event cannot be easily distinguished (see Nutman et al., 1993; Friend and Nutman, 2005a).

Collectively, the presence of fold and thrust structures, major shear zones separating tectonic blocks (or terranes), accretionary prisms (e.g., the Isua, Storø, Tartoq supracrustal belts), and subduction zone and MORB trace element signatures (Polat et al., 2011a; Szilas et al., 2012a, 2012b, 2013b) are collectively consistent with the growth of the Archean craton in West Greenland along convergent plate boundaries (Figs. 16, 17).

7. Are supracrustal belts and anorthosite complexes in West Greenland fragments of Archean ophiolites?

In the framework of the theory of plate tectonics, ophiolites have been considered as the fragments of oceanic crust and uppermost mantle, recording the opening and closure of ancient oceans (Şengör, 1990; Şengör and Natal'in, 2004; Dilek and Furnes, 2014). Several recent studies (Kusky, 2004; Şengör and Natal'in, 2004; Dilek and Polat, 2008; Dilek and Furnes, 2011; Furnes et al., 2015) have shown that the classical Penrose ophiolite definition (Anonymous, 1972), due to its major limitations, should not be used as a guide to define ophiolites in poly-deformed and metamorphosed Precambrian orogenic belts, particularly in Archean cratons. Dilek and Furnes (2011) redefined ophiolites as "suites of temporally and spatial associated ultramafic to felsic rocks related to separate melting episodes and processes of magmatic differentiation in particular tectonic environments". They divided ophiolites into two major types: (1) subduction-related ophiolites forming in backarc, forearc and arc tectonic settings; and (2) subduction-unrelated ophiolites being generated in rifted continental margins, mid-ocean ridges and oceanic plateaus. According to Furnes et al. (2015), the majority (>80%) of Archean greenstone belts are subduction-related ophiolites.

The Altaids of Central Asia represent the largest Paleozoic accretionary complex in the world (Şengör et al., 1993, 2014; Şengör and Natal'in, 1996) and contain numerous slices of oceanic lithosphere (ophiolite). Şengör and Natal'in (2004) used the term "ophirag" to define the dismembered fragments of ophiolites that are tectonically dispersed in orogenic belts and suggested that the Altaids display many geological similarities to Archean granitoid-greenstone terranes. The Eoarchean to Mesoarchean supracrustal belts and layered anorthositic complexes in the Archean craton of West Greenland can be considered as Archean counterparts of the ophirags

in the Altaids. These supracrustal belts and anorthositic complexes represent the tectonic slices of mainly Archean suprasubduction zone oceanic crust corresponding to the fragments of Archean subduction-related ophiolites of Furnes et al. (2015). Like the ophiolites in the Altaids, the supracrustal rocks and anorthositic complexes in the Archean craton of West Greenland do not display a well-defined, continuous, narrow zones or map patterns (Figs. 1-3). Rather, they tend to occur as variably oriented lenses, isoclinal folds, refolded isoclinal folds, sheath folds, and fold hooks and forks in bifurcating shear zones. These fold and shear zone patterns reflect a complex, heterogeneous, poly-phase deformation involving shearing, folding, truncation and transposition processes, resulting from several generations of overprinting deformation.

We do not mean that all Archean supracrustal belts are fragments of ophiolites. It is clear that Archean supracrustal belts that were emplaced on older continental crust such as the Neoarchean (2700 Ma) Kambalda supracrustal belt, Western Australia (Chauvel et al., 1985; Compston, et al., 1986; Lesher and Arndt, 1995) are not fragments of Archean ophiolite.

8. Gravity-driven sinking, sagduction, dripping, delamination, and diapiric rising models

Over the past forty years, one school of studies has proposed non-uniformitarian models to explain the geology of Archean cratons (e.g., Hamilton, 1998, 2013; Bédard, 2006; Robin and Bailey, 2009; Johnson et al., 2014; Thébaud and Rey, 2013; Moore and Webb, 2013; François et al., 2014; Gerya, 2014, and references therein). These models can collectively be called “gravity-driven sinking, sagduction, dripping, delamination, diapiric rising, crustal overturn, and heat pipe model”. The model name has expanded with time, as the proponents invoked new names to explain their models. The majority of these models are based mainly on numerical simulations rather than field observations. Although numerical simulations can provide significant insight

into understanding Archean tectonic processes (e.g., Hynes, 2014), given that their outcome strongly depends upon input parameters and boundary conditions set for the models, they need to be tested against geological observations (see Burke, 2011). These models assume that Archean greenstone belts were generated as either continental flood basalts (e.g., Thebaud and Rey, 2013) or oceanic plateaus (Bédard, 2006), or both. Because of density difference between mafic to ultramafic greenstones and felsic continental crust (TTG), these models assume that greenstones sink, metamorphose and melt to generate TTGs. The rise of TTG melts as diapirs generates basin and dome structures (Thebaud and Rey, 2013). Continued melting of greenstones at the base of the crust generates more TTG melts and denser restite (e.g., pyroxenite, eclogite) that eventually delaminate and recycle into the mantle (Bédard, 2006).

These models have no modern and Archean analogs and a number of major shortcomings. First, they are inconsistent with overwhelming field, structural, geochronological, and geochemical data obtained over the last four decades from the Archean craton of West Greenland specifically, and with those collected from other Archean cratons in general (e.g., Sleep, 1992; Stott, 1997; de Wit, 1998; Percival et al., 2006, 2012; Kusky et al., 2014; Furnes et al., 2013, 2015). Second, they are based on the assumption that the geological properties of Archean continents were very different from those of modern Earth. However, Burke and Kidd (1978) and Burke et al. (1986) showed that this assumption is likely to be incorrect. Third, they require the presence of pre-existing continental crust (protocrust) onto which a thick pile of Archean volcanic rocks were emplaced (Robin and Bailey, 2009), but they do not explain how the protocrust was generated in the first place. No pillow basalts have ever been recognized in continental flood basalts. Fourth, they cannot readily explain the recycling of water into the Archean upper mantle (see Polat et al., 2012; Polat, 2012), because Archean flood basalts

emplaced on continental crust would not have been as hydrated as those forming in oceanic crust. Petrogenesis of Archean layered anorthosite complexes requires hydrous melts (Polat et al., 2009b, 2012; Rollinson et al., 2010; Hoffmann et al., 2012). Subduction of altered oceanic crust is the most efficient mechanism for recycling water into the mantle (Savage, 2012). Fifth, Archean continental crust could not grow laterally and TTGs could not have been generated over millions of years without subduction of hydrated oceanic crust (see Campbell and Taylor, 1983; Burke, 2011; Arndt, 2013; Martin et al., 2014). Sixth, over 1000 km long, fault-bounded lithotectonic assemblages (e.g., the Superior Province, see Sleep, 1992; Stott, 1997; Percival et al., 2006, 2012) cannot be generated by sinking, sagduction, dripping, delamination, diapiric rising and crustal overturn processes. Seventh, these models cannot account for the presence of boninites, adakites, high-magnesian andesites, arc picrites, and high-Nb basalts in Archean greenstone belts (Polat and Kerrich, 2006). Eighth, these models cannot explain similarities in the formation of metallogenic ore deposits and their host rock associations in the Archean and Phanerozoic (Kerrick and Wyman, 1990; Kolb et al., 2013; Garde et al., 2012).

Table 1 presents a list of major Precambrian layered mafic to ultramafic intrusions (e.g., Bushveld, Stillwater), and Phanerozoic ophiolites (e.g., Oman, Bay of Island; Troodos), oceanic plateaus (Ontong Java, Caribbean), and continental flood basalts (e.g., Siberian traps, Deccan traps, Parana basalts). Despite their great thickness and density, they have not sunk into the lower crust and overturned yet, suggesting that the “sinking, sagduction, dripping, delamination, diapiric rising and crustal overturn” processes are not suitable for the Earth, at least since the mid to late Archean.

In summary, plate tectonics has not only shaped the evolution of the Earth’s mantle and crust since the early Archean (Burke, 2011; Nutman et al., 2015a) but also has played a major

role in biological evolution and climate change. The theory of plate tectonics provides a unifying and self-consistent explanation for the origins of structures, and magmatic, metamorphic and sedimentary rocks in the Earth's crust (Polat, 2014). It also provides the most efficient and simplest mechanism to explain heat dissipation from the mantle, hydration and recycling of the oceanic crust, formation of continental rifts, orogenic belts, sedimentary basins, accretionary complexes, fold and thrust belts, ophiolites and metamorphic belts, and the geochemical compositions of igneous rocks (Şengör, 1990; Hofmann, 1997; Kellogg et al., 1999; Sobolev et al., 2000; Schaefer et al., 2002; Frisch et al. 2011). The non-uniformitarian models assume a static early Earth despite higher mantle temperatures in the Archean. In contrast, the uniformitarian plate tectonic models propose a dynamic, permobile early Earth (Burke et al., 1976) and make sense of a huge amount of structural, lithological, geochemical, geochronological and petrological data obtained from Archean greenstone-granitoid terranes in all major continents over the past forty years (Polat et al., 2011a; Percival et al., 2012; Arndt, 2013; Kusky et al., 2014; Turner et al., 2014, Backeberg et al., 2014; Wang et al., 2013).

9. Structural and melting patterns in the Mesozoic Sulu orogen

A detailed discussion of the tectonic evolution of the Mesozoic Sulu orogenic belt, China, is beyond the scope and objective of this study. The main objective of this section is to compare the style of deformation and formation of felsic rocks through partial melting of mafic metamorphic rocks in the newly-discovered outcrops in the Yangkou Bay/General's Hill area of the Sulu orogenic belt (Figs. 18, 19) (Wang et al., 2010, 2014), with those described from the Archean craton of West Greenland (Figs. 4-17).

The Mesozoic Sulu orogenic belt is the eastern extension of the Qinling-Dabie orogenic belt and exposed mainly in the Shandong Peninsula (Meng and Zhang, 2000; Wang et al., 2010, 2014). The belt is well known for its ultrahigh pressure (UHP) metamorphic rocks, consisting mainly of coesite-bearing eclogites. The belt originated through a continent-continent collision between the Yangtze and North China cratons (Wang et al., 2010, 2014). The timing of the collision, and structural, metamorphic and magmatic characteristics of the Sulu subduction system are subjects of recent extensive research (Cheng et al., 2000, Liu et al., 2005; Hacker et al., 2009; Ratschbacher et al., 2006; Wang et al., 2010, 2014). The subduction of Paleozoic oceanic lithosphere beneath the North China craton resulted in the underthrusting of the leading edge of the Yangtze craton beneath the Dabie-Sulu orogen and the North China craton and intervening Qinling microcontinent in some parts of the orogen. This subduction led the formation of UHP assemblages in the Sulu orogenic belt (Wang et al., 2010). The Sulu orogenic belt consists predominantly of greenschist to amphibolite facies metamorphic rocks, with rare late Triassic coesite-bearing eclogites such as those exposed at Yankou Bay (Ames et al., 1996; Liou and Zhang, 1996). Geochronological studies of the UHP metamorphic rocks have shown that the peak metamorphism took place at about 230 Ma (see Wang et al., 2014).

Wang et al. (2014) carried out detailed structural, petrographic, geochemical and geochronological studies on retrogressed, migmatitic eclogites at General's Hill, near Diaolongzui village, about 2 km south of Diaolongzui, Yangkou Bay (Figs. 18, 19). The exposures of the General's Hill eclogite are characterized by strongly foliated, sheared and complexly folded eclogite and amphibolite dispersed within partial melt veins and layers of felsic leucosome (Fig. 20). Wang et al. (2010) showed that the partial melting of eclogites and

797 their retrogressed counterparts (amphibolites) was syn-tectonic and melts migrated along micro-
798 veins, foliation planes, fold hinges and extensional shear planes (Fig. 19).

799 Structures and relationships between the host rocks and melts at General's Hill are
800 remarkably similar to those from the much older rocks in Greenland, suggesting that similar
801 physical processes were operating in the genesis of ca. 2.8-3.0 Ga rocks in Greenland, and
802 Mesozoic rocks in the Sulu orogen. The General's Hill outcrops show an eclogitic migmatite,
803 where the light-colored rocks in Figure 20 are the leucosome, and the black to red-colored rocks
804 are the retrogressed eclogite forming melanosome and restite. Detailed studies (e.g., Wang et al.,
805 2014) show that the melts first form as small droplets along crystal grain boundaries, then merge
806 along microfaults and shear zones to accumulate in areas where the stress is low, then merge to
807 form large channels where the melt can migrate to higher levels in the crust. Similar to the
808 examples from Greenland (Figs. 14, 15), at General's Hill the melting has enhanced the
809 deformation, and the deformation has helped to concentrate the melts in low strain zones such as
810 fold hinges, extensional boudin necks, until eventually elastic-style folds become isolated from
811 each other in melt channels where the leucosome flows and merges with other melt channels to
812 form larger dikes (Fig. 20).

813 Geochemical analysis of the felsic rocks at General's Hill indicates that they are dacitic to
814 rhyolitic in composition with a calc-alkaline arc affinity. A wide spectrum of REE patterns and
815 variations in major and trace element abundances in both the felsic leucosome and mafic residue
816 are consistent with multiple melting events (Wang et al., 2014). Compositionally, the felsic rocks
817 are similar to the upper continental crust, suggesting a genetic link between subduction zone
818 geodynamic and petrogenetic processes and the origin of continental crust.

The folds in the outcrops of Diaolongzui display a variety of geometries and interference patterns, including refolded, transposed and isolated isoclinal folds, and rootles, hook- and fork-shaped folds (Figs. 19, 20). As shown in Figures 2-17, the folding style and mechanisms of melt extraction in the Sulu orogenic belt and those in the Archean craton of West Greenland are remarkably similar, suggesting that they were produced by similar geological processes.

10. Conclusions

On the basis of field observations presented in this contribution, and structural, geochronological and geochemical data obtained from the Archean craton of West Greenland over past four decades, the following conclusions and implications are drawn:

1. The Archean craton of West Greenland is characterized by Eoarchean (3850 Ma) to Neoarchean (2550 Ma) terranes (tectonic blocks) separated by mylonitic shear zones that represent suture zones along which Archean oceans were closed. The final tectonic assembly of the craton took place through multiple, horizontal accretionary processes in the late Archean between 2750 and 2600 Ma.
2. The tectonic terranes are composed mainly of TTG gneisses and granites (ca. 80%), and supracrustal rocks (greenstone belts) and layered anorthositic complexes (ca. 20%). Except for the late- to post-tectonic granites (e.g., the ca. 2550 Ma Qôrqt granites), all these rock types underwent multiple phases of deformation and greenschist to granulite facies metamorphism at convergent plate boundaries, consistent with the growth of Archean continental crust mainly in subduction zones.
3. The supracrustal belts represent relict accretionary prisms (e.g., the Eoarchean Isua and Mesoarchean Tartoq belts) or fragments of island arc, forearc or backarc oceanic crust (e.g.,

Mesoarchean Ivisaartoq, Qussuk-Bjørneøen belts) are interpreted as fragments of Archean ophiolites.

4. The layered anorthositic complexes (e.g., the Fiskebøl Complex) were derived from hydrous mantle sources and formed as suprasubduction zone oceanic crust.

5. The style of deformation (e.g., fold patterns, shearing) on centimetre to metre scale shear zones is similar to those developed on regional scale, suggesting that Archean terranes can be defined as collages of lithotectonic assemblages. The presence of widespread shearing throughout the terranes is consistent with the growth of the Archean craton of West Greenland by tectonic accretion. The map patterns of the supracrustal rocks in the Archean craton West Greenland are similar to those in the Paleozoic Altaid orogenic belt.

6. Partial melting of supracrustal belts in thickened arcs played an important role in the formation of Archean continental crust.

7. The style of deformation and generation of felsic rocks through melting of mafic rocks in the Archean craton of West Greenland and Mesozoic Sulu orogenic belt in eastern China are similar, suggesting that the mechanism of continental crust formation in the Archean and Phanerozoic is similar.

8. Tectonic, magmatic, and metamorphic processes and field relationships recorded in the Archean craton of West Greenland, as well as those in other Archean cratons and post-Archean orogenic belts, are collectively inconsistent with the operation of non-uniformitarian, gravity-driven sinking, sagduction, dripping, delamination, diapiric rising, crustal overturn, and heat pipe models over past four billion years in Earth history.

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References

- Adam, J., Rushmer, T., O'Neil, J., Francis, D., 2012. Hadean greenstones from the Nuvvuagittuq fold belt and the origin of the Earth's early continental crust. *Geology* 40, 363–366.
- Allaart, J.H., 1976. The pre-3760 m.y. old supracrustal rocks of the Isua Area, Central West Greenland, and the associated occurrence of quartz-banded ironstone. In: B.F., Windley (Ed.), *The Early History of the Earth*. John Wiley and Sons, London, pp. 177–189.
- Ames, L., Zhou, G., Xiong, B., 1996. Geochronology and geochemistry of ultra-high pressure metamorphism with implications for collision of the Sino-Korean and Yangtze cratons, central China. *Tectonics* 15, 472–489.
- Amiguet, E., Reynard, B., Caracas, R., Van de Moortele, Hilairt, N., Wang, N., 2012. Creep of phyllosilicates at the onset of plate tectonics. *Earth and Planetary Science Letters* 345–348, 142–150.
- Andersen, L.S., 1974. Rapport over geologien mellem Frederkshåbs Isblink og Quvnilik Fjord – Vest Grønland. Unpublished Ph.D. thesis, Copenhagen University, 259 pp.

888 Andersen, L.S., Friend, C.R.L., 1973. Structure of the Ravns Storø amphibolite belt in the
889 Fiskeneset region. *Rapport Grønlands Geologiske Undersøgelse* 51, 37–40.

890 Anonymous, 1972. Penrose field conference on Ophiolites. *Geotimes* 17, 24–25.

891 Appel, P.W.U., Fedo, C.M., Moorbath, S., Myers, J.S., 1998. Recognizable primary volcanic and
892 sedimentary features in a low-strain domain of the highly deformed, oldest known (≈ 3.7 -3.8
893 Gyr) Greenstone Belt, Isua, West Greenland. *Terra Nova* 10, 57–62.

894 Appel, P.W.U., Polat, A., Frei, R., 2009. Dacitic ocelli in mafic lavas, 3.8-3.7 Ga Isua greenstone
895 belt, West Greenland: Geochemical evidence for partial melting of oceanic crust and magma
896 mixing. *Chemical Geology* 258, 105–124.

897 Appel, P.W.U., Secher, K., 1984. On gold mineralization in the Precambrian Tartoq Group, SW
898 Greenland. *Journal of the Geological Society of London* 141, 273–278.

899 Arndt, N.T., 2013. The formation and evolution of the continental crust. *Geochemical*
900 *Perspectives* 2, 405–528.

901 Ashwal, L.D. 1993. *Anorthosites*. Springer-Verlag, Berlin, 422 pp.

902 Baadsgaard, H., Nutman, A.P., Bridgwater, D., 1986. Geochronology and isotopic variation of
903 the early Archean Amitsoq gneisses of the Isukasia area, southern West Greenland.
904 *Geochimica et Cosmochimica Acta* 50, 2173–2183.

905 Backeberg, N.R., Rowe, C.D., van Hinsberg, V.J., Bellefroid, E.J., 2014. Structural and
906 metamorphic evidence for Mesoarchean subduction in the Finlayson Lake greenstone belt,
907 Superior Province, Ontario. *Precambrian Research* 249, 100–114.

908 Bédard, J.H., 2006. A catalytic delamination-driven model for coupled genesis of Archaean crust
909 and sub-continental lithospheric mantle. *Geochimica et Cosmochimica Acta* 70, 1188–1214.

910 Berthelsen, A., Henriksen, N., 1975. Geological map of Greenland, 1:100,000 Ivittuut 61 V.1
 911 Syd (with description), Geological Survey of Greenland, Copenhagen.

912 Bridgwater, D., McGregor, V.R., Myers, J.S., 1974. A horizontal tectonic regime in the
 913 Archaean of Greenland and its implications for early crustal thickening. *Precambrian*
 914 *Research* 1, 179–197.

915 Bridgwater, D., Keto, L., McGregor, V.R., Myers, J.S. 1976. Archean gneiss complex of
 916 Greenland. In: Escher A., Watt, W.S., (Eds.), *Geology of Greenland*. Copenhagen, Geological
 917 Survey of Greenland, 21–75.

918 Burke, K., 2011. Plate tectonics, the Wilson cycle, and mantle plumes: geodynamics from the
 919 top. *Annual Review of Earth and Planetary Sciences* 39, 1–29.

920 Burke, K., Dewey, J., Kidd, W.S.F., 1976. Dominance of horizontal movements, arc and
 921 microcontinental collisions during the later permobile regime. In: Windley, B.F. (Ed.), *The*
 922 *Early History of the Earth*. Wiley, London, pp. 113-129.

923 Burke, K., Kidd, W.S.F., 1978. Were Archean continental geothermal gradients much steeper
 924 than those of today? *Nature* 272, 240–241.

925 Burke, K., Kidd, W.S.F., Kusky T.M., 1986. Archean foreland basin tectonics in the
 926 Witwatersrand, South Africa. *Tectonics* 5, 439–56.

927 Campbell, I.H., Taylor, S.R., 1983. No water, no granites – no granites, no continents.
 928 *Geophysical Research Letters* 10, 1061–1064.

929 Chauvel, C., Dupre, B., Jenner, G., 1985. The Sm-Nd age of Kambalda volcanic is 500 Ma too
 930 old. *Earth and Planetary Science Letters* 74, 315-324.

931 Cengija, S., 2010. Geochemical and Petrological Analysis of Ikatoq and Bjornesund Greenstone
 932 belts in Southern Greenland. Unpublished MSc thesis, University of Windsor, 58 pp.

933 Chadwick, B., 1985. Contrasting styles of tectonism and magmatism in the late Archean crustal
 934 of the northeastern part of the Ivisârtoq region, inner Godthåbsfjord, southern west Greenland.
 935 Precambrian Research 27, 215–238.

936 Chadwick, B., 1990. The stratigraphy of a sheet of supracrustal rocks within high-grade
 937 orthogneisses and its bearing on Late Archaean structure in southern West Greenland. Journal
 938 of the Geological Society, London, 147, 639–652.

939 Cheng, Y.Q., Liu, D.Y., Williams, I.S., Jian, P., Zhuang, Y.X., Gao, T.S., 2000. SHRIMP U-Pb
 940 dating of zircons of a dark-colored eclogite and a garnet-bearing gneissic-granitic rock from
 941 Bixiling, eastern Dabie area, Anhui Province: isotope chronological evidence of
 942 Neoproterozoic UHP metamorphism. Acta Geologica Sinica 74, 748–765.

943 Compston, W., Williams, I.S., Campbell, I.H., Gresham, J.J., 1986. Zircon xenocrysts from the
 944 Kambalda volcanic: age constraints and direct evidence for older continental crust below the
 945 Kambalda-Norseman greenstones. Earth and Planetary Science Letters 76, 299–311.

946 Crowley, J.L., 2002. Testing the model of late Archean terrane accretion in southern West
 947 Greenland: a comparison of the timing of geological events across the Qarliit nunaat fault,
 948 Buksefjorden region. Precambrian Research 116, 57–79.

949 Crowley, J.L., 2003. U-Pb geochronology of 3810–3630 Ma granitoid rocks south of the Isua
 950 greenstone belt, southern West Greenland. Precambrian Research 126, 235–257.

951 de Wit, M.J., 1998. On Archean granites, greenstones, cratons, and tectonics: does the evidence
 952 demand a verdict? Precambrian Research 91, 181–226.

953 de Wit, M., Furnes, H., 2013. Earth's oldest preserved unconformity — Prospect of a beginning
 954 in the tectono-sedimentary continental cycle? Gondwana Research 23, 429–435.

955 Dilek, Y., Furnes, H., 2011. Ophiolite genesis and global tectonics: Geochemical and tectonic
 956 fingerprinting of ancient oceanic lithosphere. *Geological Society of America Bulletin* 123,
 957 387–411.

958 Dilek, Y., Furnes, H., 2014. Ophiolites and their origins. *Elements* 10, 93-100.

959 Dilek, Y., Polat, A., 2008. Suprasubduction zone ophiolites and Archean tectonics. *Geology* 36,
 960 431-432.

961 Dostal, J., Mueller, W.U., 2013. Deciphering an Archean mantle plume: Abitibi greenstone belt,
 962 Canada. *Gondwana Research* 23, 493–505.

963 Dyck, B., Reno, B.L., Kokfelt, T.F., 2015. The Majorqaaq Belt: A record of Neoarchean
 964 orogenesis during final assembly of the North Atlantic Craton, southern West Greenland.
 965 *Lithos* 220–223, 253–271.

966 Dymek, R.F., Owens, B.R., 2001. Chemical assembly of Archean anorthosites from amphibolite-
 967 and granulite-facies terranes, SW Greenland. *Contributions to Mineralogy and Petrology* 141,
 968 513-528.

969 Dziggel, A., Diener, J.F.A., Kolb, J., Kokfelt, T.F., 2014. Metamorphic record of accretionary
 970 processes during the Neoarchean: The Nuuk region, Southern West Greenland. *Precambrian*
 971 *Research* 242, 22–38.

972 Ernst, R.E., Bleeker, W., Söderlund, U., Kerr, A.C., 2013. Large Igneous Provinces and
 973 supercontinents: Toward completing the plate tectonic revolution. *Lithos* 174, 1–14.

974 Escher, J.C., Myers, J.S., 1975. New evidence concerning the original relationships of early
 975 Precambrian volcanic and anorthosites in the Fiskensæset region, southern West Greenland.
 976 *Grønlands Geologiske Undersøgelse Rapport* 75, 72–76.

977 Escher, J.C., Pulvertaft, T.C.R., 1995. Geological map of Greenland, 1: 2 500 000. Copenhagen:
 978 Geological Survey of Denmark.

979 Evans, D.M., King, A.R., 1993. Sediment and shear-hosted gold mineralization of the Tartoq
 980 Group supracrustals, southwest Greenland. *Precambrian Research* 62, 61–82.

981 Fedo, C.M., 2000. Setting and origin for problematic rocks from the >3.7 Ga Isua greenstone
 982 belt, southern west Greenland: Earth's oldest coarse clastic sediments. *Precambrian Research*
 983 101, 69-78.

984 Frisch, W., Meschede, M., Blakey, R., 2011. Plate Tectonic: Continental Drift and Mountain
 985 Building. Springer-Verlag, Berlin, pp. 212.

986 Frei, R., Polat, A., Meibom, A., 2004. The Hadean upper mantle conundrum: evidence for source
 987 depletion and enrichment from Sm–Nd, Re–Os, and Pb isotopic compositions in 3.71 Gy
 988 boninite-like metabasalts from the Isua Supracrustal belt, Greenland. *Geochimica et*
 989 *Cosmochimica Acta* 68, 1645–1660.

990 Friend, C.R.L., 1975. The geology and geochemistry of the Preketilidian basement complex in
 991 the Ravns Storø area, Fiskenæsset region, southern West Greenland. Unpublished Ph.D.
 992 thesis, University London, 233 pp.

993 Friend, C.R.L., Bennett, V.C., Nutman, A.P., 2002. Abyssal peridotites > 3800 Ma from
 994 southern West Greenland: field relationships, petrography, geochronology, whole-rock and
 995 mineral chemistry of dunite and harzburgite inclusions in the Itsaq Gneiss Complex.
 996 *Contributions to Mineralogy and Petrology* 143, 71–92.

997 Friend, C.R.L., Nutman, A.P., 1991. Refolded nappes during late Archean terrane assembly,
 998 Godthåbsfjord, southern West Greenland. *Journal of the Geological Society, London*, 148,
 999 507–519.

1000 Friend, C.R.L., Nutman, A.P., 2001. U–Pb zircon study of tectonically-bound blocks of 2940–
 1001 2840 Ma crust with different metamorphic histories, Paamiut region, South-West Greenland:
 1002 Implications for the tectonic assembly of the North Atlantic craton. *Precambrian Research*
 1003 105, 143–164.

1004 Friend, C.R.L., Nutman, A.P., 2005a. New pieces to the Archean jigsaw puzzle in the Nuuk
 1005 region, southern West Greenland: steps in transforming a simple insight into a complex
 1006 regional tectonothermal model. *Journal of the Geological Society, London* 162, 147–162.

1007 Friend, C.R.L., Nutman, A.P., 2005b. Complex 3670–3500 Ma episodes superimposed on
 1008 juvenile crust between 3850 and 3690 Ma, Itsaq Gneiss Complex, Southern West Greenland.
 1009 *Journal of Geology* 113, 375–397.

1010 Friend, C.R.L., Nutman, A.P., McGregor, V.R., 1987. Late-Archaean tectonics in the
 1011 Færingehavn–Tre Brødre area, south of Buksefjorden, southern West Greenland. *Journal of*
 1012 *the Geological Society, London*, 144, 369–376.

1013 Friend, C.R.L., Nutman, A.P., McGregor, V.R., 1988. Late Archean terrane accretion in the
 1014 Godthåb region, southern West Greenland. *Nature* 335, 535–538.

1015 Friend, C.R.L., Nutman, A.P., Baadsgaard, Kinney, P.D., McGregor, V.R., 1996. Timing of late
 1016 Archean terrane assembly, crustal thickening and granite emplacement in the Nuuk region,
 1017 southern West Greenland. *Earth and Planetary Science Letters* 142, 353–365.

1018 Friend, C.R.L., Nutman, A.P., Bennett, V.C., Norman, M.D., 2008. Seawater-like trace element
 1019 signatures (REE + Y) of Eoarchean chemical sedimentary rocks from southern West
 1020 Greenland, and their corruption during high-grade metamorphism. *Contributions to*
 1021 *Mineralogy and Petrology* 155, 229–246.

1022 François, C., Philippot, P., Rey, P., Rubatto, D., 2014. Burial and exhumation during Archean
 1023 sagduction in the East Pilbara Granite-Greenstone Terrane. *Earth and Planetary Science*
 1024 *Letters* 396, 235–251.

1025 Furnes, H., de Wit, M., Staudigel, H., Rosing, M., Muehlenbachs, K., 2007. A vestige of Earth's
 1026 oldest ophiolite. *Science* 315, 1704–1707.

1027 Furnes, H., de Wit, M.J., Robins, B., 2013. A review of new interpretations of the
 1028 tectonostratigraphy, geochemistry and evolution of the Onverwacht Suite, Barberton
 1029 Greenstone Belt, South Africa. *Gondwana Research* 23, 403–428.

1030 Furnes, H., Rosing, M., Dilek, Y., de Wit, M., 2009. Isua supracrustal belt (Greenland) —A
 1031 vestige of a 3.8 Ga suprasubduction zone ophiolite, and the implications for Archean geology.
 1032 *Lithos* 113, 115–132.

1033 Furnes, H., Dilek, Y., de Wit, M., 2015. Precambrian greenstone sequences represent different
 1034 ophiolite types. *Gondwana Research* 27, 649–685.

1035 Garde, A.A., 1990. Thermal granulite-facies metamorphism with diffuse retrogression in
 1036 Archaean orthogneisses, Fiskefjord, southern West Greenland. *Journal of Metamorphic*
 1037 *Geology* 8, 663–682.

1038 Garde, A.A., 1997. Accretion and evolution of an Archaean high-grade grey gneiss–amphibolite
 1039 complex: the Fiskefjord area, southern West Greenland. *Bulletin Grønlands Geologiske*
 1040 *Undersøgelse* 177, 115 pp.

1041 Garde, A.A., 2007. A Mid-Archean island arc complex in the eastern Akia terrane,
 1042 Godthåbsfjord, southern West Greenland. *Journal of the Geological Society, London*, 164,
 1043 565–579.

1044 Garde, A.A., Dyck, B., Esbensen, K., Johansson, L., Möller, C., 2014. The Finnefjeld domain,
 1045 Maniitsoq structure, West Greenland: Differential rheological features and mechanical
 1046 homogenisation in response to impacting? *Precambrian Research* 255, 791-808.

1047 Garde, A.A., Whitehouse, M., Christensen, R., 2012. Mesoarchean epithermal gold
 1048 mineralization preserved at upper amphibolite-facies grade, Qussuk, southern West
 1049 Greenland. *Economic Geology* 107, 881-908.

1050 Gerya, T., 2014. Precambrian geodynamics: Concepts and models. *Gondwana Research* 25, 442–
 1051 463.

1052 Glendenning, M., 2011. Mapping and petrographic analysis of the lithology of Akuliaq
 1053 Peninsula, Paamiut Region, Southwest Greenland. Geological Survey of Denmark and
 1054 Greenland, Ministry of Climate and Energy Report 2011/114, 79-115.

1055 Hacker, B.R., Wallis, S.R., McWilliams, M.O., Gans, P.B., 2009. $^{40}\text{Ar}/^{39}\text{Ar}$ constraints on the
 1056 tectonic history and architecture of the ultrahigh-pressure Sulu orogen. *Journal of*
 1057 *Metamorphic Geology* 27, 827-844.

1058 Hall, R.P., 1980. The tholeiitic and komatiitic affinity of Malene metavolcanic amphibolites
 1059 from Ivisaartoq, southern West Greenland. *Grønlands Geologiske Undersøgelse Rapport* 97,
 1060 20 pp.

1061 Hall, R.P., Friend, C.R.L., 1979. Structural evolution of the Archean rocks in Ivisârtoq and the
 1062 neighbouring inner Godthåbsfjord region, southern West Greenland. *Geology* 7, 311–315.

1063 Hamilton, W.B., 1998. Archean magmatism and deformation were not products of plate
 1064 tectonics. *Precambrian Research* 91, 143–179.

1065 Hamilton, W.B., 2013. Evolution of the Archean Mohorovičić discontinuity from a
 1066 synaccretionary 4.5 Ga protocrust. *Tectonophysics* 609, 706–733.

1067 Hanmer, S., Hamilton, M.A., Crowley, J.L., 2002. Geochronological constraints on Paleoproterozoic
 1068 thrust-nappe and Neoproterozoic accretionary tectonics in southern West Greenland.
 1069 *Tectonophysics* 350, 255–271.

1070 Hanmer, S., Greene D.C., 2002. A modern structural regime in the Paleoproterozoic (~3.64); Isua
 1071 Greenstone Belt, southern West Greenland. *Tectonophysics* 346, 201–222.

1072 Hastie, E.C.G., 2011. Mapping and Structural Analysis of the Akuliaq
 1073 Peninsula, near Paamut, SW Greenland. Geological Survey of Denmark and Greenland,
 1074 Ministry of Climate and Energy Report 2011/114, 49–78.

1075 Hawkins, J.W., 2003. Geology of supra-subduction zones: Implications for the origin of
 1076 ophiolites. In: Dilek, Y., Newcomb, S., (Eds.), *Ophiolite Concept and the Evolution of*
 1077 *Geological Thought*. Geological Society of America Special Paper 373, 227–268.

1078 Hiess, J., Bennett, V.C., Nutman, A.P., Williams, I.S., 2009. In situ U–Pb, O and Hf isotopic
 1079 compositions of zircon from Eoarchean tonalite and felsic volcanic rocks, Itsaq Gneiss
 1080 Complex, southern West Greenland: New constraints on the source materials for the early
 1081 crust. *Geochimica et Cosmochimica Acta* 73, 4489–4516.

1082 Hiess, J., Bennett, V.C., Nutman, A.P., Williams, I.S., 2011. Archaean fluid-assisted crustal
 1083 cannibalism recorded by low $\delta^{18}\text{O}$ and negative $\varepsilon_{\text{Hf}}(\text{T})$ isotopic signatures of West Greenland
 1084 granite zircon. *Contributions to Mineralogy and Petrology* 161, 1027–1050.

1085 Higgins, A.K., 1968. The Tartoq Group on Nuna Qaqertoq and in the Iterdlak area, South-West
 1086 Greenland: Rapport Grønlands Geologiske Undersøgelse, 17 pp.

1087 Higgins, A.K., 1990. Descriptive text to 1:100000 sheets Neria 61 V.1 N and Midternæs 61 V.2
 1088 N. Geological Survey of Greenland, 23 pp.

1089 Hofmann, A.W., 1997. Mantle geochemistry: the messages from oceanic volcanism. *Nature* 385,
 1090 219-229.

1091 Hoffmann, J.E., Münker, C., Næraa, T., Rosing, M.T., Herwartz, D., Garbe-Schönberg, D.,
 1092 Svahnberg, H., 2011. Mechanisms of Archean crust formation inferred from high-precision
 1093 HFSE systematics in TTGs. *Geochimica et Cosmochimica Acta* 75, 4157–4178.

1094 Hoffmann, J.E., Münker, C., Polat, A., König, S., Mezger, K., Rosing, M.T., 2010. Highly
 1095 depleted Hadean mantle reservoirs in the sources of early Archean arc-like rocks, Isua
 1096 supracrustal belt, SW-Greenland. *Geochimica et Cosmochimica Acta* 74, 7236–7260.

1097 Hoffmann, J.E., Svahnberg, H., Piazzolo, S., Scherstén, A., Münker, C., 2012. The geodynamic
 1098 evolution of Mesoarchean anorthosite complexes inferred from the Naajat Kuuat Complex,
 1099 southern West Greenland. *Precambrian Research* 196–197, 149–170.

1100 Hoffmann, J.E., Nagel, T.J., Münker, C., Næraa, T., Rosing, M.T., 2014. Constraining the
 1101 process of Eoarchean TTG formation in the Itsaq Gneiss Complex, southern West Greenland.
 1102 *Earth and Planetary Science Letters* 388, 374–386.

1103 Hollis, J.A., (Ed.) 2005. Greenstone belts in central Godthåbsfjord region, southern West
 1104 Greenland: Geochemistry, geochronology and petrology arising from 2004 field work, and
 1105 digital map data. *Danmarks Og Grønlands Geologiske Undersøgelse Rapport* 42, 214 pp.

1106 Hollis, J.A., van Gool, J.A.M., Steenfelt, A., Garde, A.A., 2004. Greenstone belts in the central
 1107 Godthåbsfjord region, southern West Greenland: Preliminary results from field work in
 1108 2004. *Danmarks Og Grønlands Geologiske Undersøgelse Rapport* 110, 110 pp.

1109 Huang, H., Fryer, B.J., Polat, A., Pan, Y., 2014. Amphibole, plagioclase and clinopyroxene
 1110 geochemistry of the Archean Fiskensæset Complex at Majorqap qâva, southwestern

1111 Greenland: Implications for Archean petrogenetic and geodynamic processes. *Precambrian*
 1112 *Research* 247, 64-91.

1113 Huang, H., Polat, A., Fryer, B.J., Appel, P.W.U., Windley, B.F., 2012. Geochemistry of the
 1114 Mesoarchean Fiskenæsset Complex at Majorqap qâva, SW Greenland: Evidence for two
 1115 different magma compositions. *Chemical Geology* 314-317, 66-82.

1116 Hynes, A., 2014. How feasible was subduction in the Archean? *Canadian Journal of Earth*
 1117 *Sciences* 51, 286–296.

1118 Irvine, T.N., 1974. Petrology of the Duke Island Ultramafic Complex Southeastern Alaska. The
 1119 Geological Society of America Memoir, Inc. 138, 240 pp.

1120 Jenner, F.E., Bennett, V.C., Nutman, A.P., Friend, C.R.L., Norman, M.D., Yaxley, G., 2009.
 1121 Evidence for subduction at 3.8 Ga: geochemistry of arc-like metabasalts from the southern
 1122 edge of the Isua Supracrustal Belt. *Chemical Geology* 261, 83–98.

1123 Johnson, T.E., Brown, M., Kaus, B.J.P., Van Tongeren, J.A., 2014. Delamination and recycling
 1124 of Archaean crust caused by gravitational instabilities. *Nature Geosciences* 7, 47–52.

1125 Kalsbeek, F., Myers, J.S., 1973. The geology of the Fiskenæsset region. Rapport Grønlands
 1126 Geologiske Undersøgelse 51, 5–22.

1127 Kalsbeek, F., Pidgeon, R.T., 1980. The geological significance of Rb-Sr whole-rock isochrons of
 1128 polymetamorphic Archean gneisses, Fiskenæsset area, southern West Greenland. *Earth and*
 1129 *Planetary Science Letters* 50, 225–237.

1130 Kamber, B.S., 2015. The evolving nature of terrestrial crust from the Hadean, through the
 1131 Archaean, into the Proterozoic. *Precambrian Research* 258, 48–82.

1132 Kamber, S.B., Moorbath, S., 1998. Initial Pb of the Amîtsoq gneisses revisited: implications for
 1133 the timing of early Archean crustal evolution in West Greenland. *Chemical Geology* 150, 19–
 1134 41.
 1135 Kamber, B.S., Moorbath, S., Whitehouse, M.J., 1998. Extreme Nd-isotope heterogeneity in the
 1136 early Archean- fact or fiction? Case histories from northern Canada and West Greenland-
 1137 Reply. *Chemical Geology* 148, 219–224.
 1138 Kellogg, L.H., Hager, B.H., van der Hilst, D.D., 1999. Compositional stratification the deep
 1139 mantle. *Science* 283, 1881-1884.
 1140 Kerrich, R., Wyman, D., 1990. Geodynamic setting of mesothermal gold deposits: An
 1141 association with accretionary tectonic regimes. *Geology* 18, 882–885.
 1142 Keto, L., Kurki, J., 1967. Report on the exploration activity at Isua 1967. Kryolitselkabet
 1143 Øresund A/S prospecting: Rapport 20024. Geological Survey of Denmark and Greenland.
 1144 Keulen, N., Næraa, T., Kokfelt, T.F., Schumacher, J.C., Scherstén, A., 2010. Zircon record of the
 1145 igneous and metamorphic history of the Fiskenæsset anorthosite complex in southern West
 1146 Greenland. *Geological Survey of Denmark and Greenland Bulletin* 20, 67-70.
 1147 Keulen, N., Schumacher, J.C., Næraa, T., Kokfelt, T.F., Scherstén, A., Szilas, K., van Hinsberg,
 1148 V.J., Schlatter, D.M., Windley, B.F., 2014. Meso- and Neo-archaeon geological history of the
 1149 Bjørnesund and Ravns Storø Supracrustal Belts, southern West Greenland: Settings for gold
 1150 enrichment and corundum formation. *Precambrian Research* 254, 36–58
 1151 Kisters, A.F.M., van Hinsberg, V.J., Szilas, K., 2012. Geology of an Archean accretionary
 1152 complex — the structural record of burial and return flow in the Tartoq Group of South West
 1153 Greenland. *Precambrian Research* 220–221, 107–122.

1154 Kolb, J., Kokfelt, T.F., Dziggel, A., 2012. Geodynamic setting and deformation history of an
 1155 Archean terrane at mid-crustal level: The Tasiusarsuaq terrane of southern West Greenland.
 1156 Precambrian Research 212–213, 34–56.

1157 Kolb, J., Dziggel, A., Schlatter, D.M., 2013. Gold occurrences of the Archean North Atlantic
 1158 craton, southwestern Greenland: A comprehensive genetic model. Ore Geology Reviews 54,
 1159 24–58.

1160 Komiya, T., Maruyama, S., Masuda, T., Nohda, S., Hayashi, M., Okamoto, K., 1999. Plate
 1161 Tectonic at 3.8–3.7 Ga: Field evidence from the Isua accretionary Complex, Southern West
 1162 Greenland. Journal of Geology 107, 515–554.

1163 Knudsen, C., van Gool, J.A.M., Østergaard, C., Hollis, J.A., Rink-Jørgensen, M., Persson, M.,
 1164 Szilas, K., 2007. Gold-hosting supracrustal rocks on Storø, southern West Greenland:
 1165 lithologies and geological environment. Geological Survey of Denmark and Greenland
 1166 Bulletin 13, 41–44.

1167 Kurth, M., Sassen, A., Suhr, G., Mezger, K., 1998. Precise ages and isotopic constraints for the
 1168 Lewis Hills (Bay of Islands Ophiolite): Preservation of an arc–spreading ridge intersection.
 1169 Geology 26, 1127–1130.

1170 Kusky, T.M., 2004. Epilogue: What if anything have we learned about Precambrian ophiolites
 1171 and early Earth processes? In: Kusky T.M. (Ed.), Precambrian Ophiolites and Related
 1172 Rocks, Developments in Precambrian Geology, Vol. 13 (K.C. Condie, Series Editor),
 1173 Elsevier B.V., Amsterdam, pp.727–637.

1174 Kusky, T.M., Li, X., Wang, Z., Fu, J., Ze, L., Zhu, P., 2014. Are Wilson Cycles preserved in
 1175 Archean cratons? A comparison of the North China and Slave cratons. Canadian Journal of
 1176 Earth Sciences 51, 297–311.

1177 Kusky, T., Polat, A., 1999. Growth of granite-greenstone terranes at convergent margins, and
 1178 stabilization of Archean cratons. *Tectonophysics* 305, 43–73.

1179 Leshner, C.M., Arndt, N.T., 1995. REE and Nd isotope geochemistry, petrogenesis and volcanic
 1180 evolution of contaminated komatiites at Kambalda, Western Australia. *Lithos* 34, 127-157.

1181 Liu, F., Liou, J.G., Xu, Z., 2005. U-Pb SHRIMP ages recorded in the coesite-bearing zircon
 1182 domains of paragneisses in the southwestern Sulu terrane, eastern China: new interpretation.
 1183 *American Mineralogist* 90, 790–800.

1184 Liou, J.G., Zhang, R.Y., 1996. Occurrences of intergranular coesite in UHP rocks from the Sulu
 1185 region, eastern China: implications for lack of fluid during exhumation. *American*
 1186 *Mineralogist* 81, 1217–1221.

1187 Lowry, D., Appel, P.W.U., Rollinson, H.R., 2003. Oxygen isotopes of an Early Archaean layered
 1188 ultramafic body, southern West Greenland: implications for magma source and post-intrusion
 1189 history. *Precambrian Research* 126, 273–288.

1190 Mann, P., Taira, A., 2004. Global tectonic significance of the Solomon Islands and Ontong Java
 1191 convergent zone. *Tectonophysics* 389, 137–190.

1192 Martin, H., Moyen, J.-F., Guitreau, M., Blichert-Toft, J., Le Pennec, J.-L., 2014. Why Archaean
 1193 TTG cannot be generated by MORB melting in subduction zones. *Lithos* 198–199, 1–13.

1194 McGregor, V.R., 1973. The early Precambrian gneisses of the Godthåb district, West Greenland.
 1195 *Philosophical Transactions of the Royal Society of London*, A273, 343–358.

1196 McGregor, V.R., Friend, C.R.L., 1992. Late Archean prograde amphibolite to granulite-facies
 1197 relations in the Fiskensæset region, Southern West Greenland. *Journal of Geology* 100, 207-
 1198 219.

1199 McGregor, V.R., Friend, C.R.L., Nutman, A.P., 1991. The late Archaean mobile belt through
1200 Godthåbsfjord, southern West Greenland: a continent-continent collision zone? *Bulletin of*
1201 *the Geological Society of Denmark* 39, 179–197.

1202 Meng, Q.R., Zhang, G.W., 2000. Geologic framework and tectonic evolution of the Qinling
1203 orogen, central China. *Tectonophysics* 323, 183–196.

1204 Moorbath, S., O’Nions, R.K., Pankhurst, R.J., 1973. Early Archean age for the Isua Iron
1205 formation, West Greenland. *Nature* 245, 138–139.

1206 Moorbath, S., Taylor, P.N., Goodwin, R., 1981. Origin of granitic magma by crustal
1207 remobilisation: Rb–Sr and Pb/Pb geochronology and isotope geochemistry of the late
1208 Archaean Qôrquut granite complex of southern West Greenland. *Geochimica et Cosmochimica*
1209 *Acta* 45, 1051–1060.

1210 Moore, W.B., Webb, A.A.G., 2013. Heat-pipe Earth. *Nature* 501, 501–505.

1211 Myers, J.S., 1976. Granitoid sheets, thrusting, and Archean crustal thickening in West
1212 Greenland. *Geology* 4, 265–268.

1213 Myers, J.S., 1985. Stratigraphy and structure of the Fiskensæset Complex, southern West
1214 Greenland. *Grønlands Geologiske Undersøgelse Bulletin* 150, 72 pp.

1215 Myers, J.S., 2001. Protoliths of the 3.7–3.8 Ga Isua greenstone belt, West Greenland.
1216 *Precambrian Research* 105, 129–141.

1217 Næraa, T., Kemp, A.I.S., Scherstén, A., Rehnström, E.F., Rosing, M.T., Whitehouse, M.J., 2014.
1218 A lower crustal mafic source for the ca. 2550 Ma Qôrquut Granite Complex in southern West
1219 Greenland. *Lithos* 192–195, 291–304.

1220 Nagel, T.J., Hoffmann, J.E., Münker, C., 2012. Generation of Eoarchean tonalitic-trondhjemitic-
1221 granodioritics from thickened mafic arc crust. *Geology* 40, 375–378.

1222 Nebel-Jacobsen, Y., Münker, C., Nebel, O., Gerdes, A., Mezger, K., Nelson, D.R., 2010.
1223 Reworking of Earth's first crust: constraints from Hf isotopes in Archean zircons from Mt.
1224 Narryer, Australia. *Precambrian Research* 182, 175–186.

1225 Nutman, A.P., 1986. The early Archean to Proterozoic history of the Isukasia area, southern
1226 West Greenland. *Geological Survey of Greenland Bulletin* 154, pp. 80.

1227 Nutman, A.P., Bennett, V.C., Friend, C.R.L., Horie, K., Hidaka, H., 2007a. ~3.850 Ma tonalities
1228 in the Nuuk region, Greenland: geochemistry and their reworking within an Eoarchean gneiss
1229 Complex. *Contributions to Mineralogy and Petrology* 154, 385–408.

1230 Nutman, A.P., Bennett, V.C., Friend, C.R.L., 2015a. The emergence of the Eoarchean proto-
1231 arc: evolution of a c. 3700 Ma convergent plate boundary at Isua, southern West Greenland.
1232 In: Roberts, N.M.W., Van Kranendonk, M., Parman, S., Shirey, S., Clift, P.D. (Eds.),
1233 *Continent Formation Through Time*. Geological Society, London, Special Publications 389,
1234 113–133.

1235 Nutman, A.P., Bennett, V.C., Friend, C.R.L., Yi, K., Lee, S.R., 2015b. Mesoarchean collision
1236 of Kapisilik terrane 3070 Ma juvenile arc rocks and >3600 Ma Isukasia terrane continental
1237 crust (Greenland). *Precambrian Research* 258, 146–160.

1238 Nutman, A.P., Bennett, V.C., Friend, C.R.L., Rosing, M.T., 1997. ~3710 and 3790 Ma volcanic
1239 sequences in the Isua (Greenland) supracrustal belt; structural and Nd isotope implications.
1240 *Chemical Geology* 141, 271–287.

1241 Nutman, A.P., Bennett, V.C., Friend, C.R.L., Norman, M.D., 1999. Meta-igneous (non-gneissic)
1242 tonalites and quartz-diorites from an extensive ca. 3800 Ma terrain south of the Isua
1243 supracrustal belt, southern West Greenland: constraints on early crust formation.
1244 *Contributions to Mineralogy and Petrology* 137, 364–388.

1245 Nutman, A.P., Christiansen, O., Friend, C.R.L., 2007b. 2635 Ma amphibolite facies gold
 1246 mineralisation near a terrane boundary (suture?) on Storø, Nuuk region, southern West
 1247 Greenland. *Precambrian Research* 159, 19-32.

1248 Nutman, A.P., Collerson, K.D., 1991. Very early Archean crustal-accretion complexes preserved
 1249 in the North Atlantic craton. *Geology* 19, 791–794.

1250 Nutman, A.P., Friend, C.R.L., 2007. Adjacent terranes with ca. 2715 and 2650 Ma high-pressure
 1251 metamorphic assemblages in the Nuuk region of the North Atlantic Craton, southern West
 1252 Greenland: Complexities of Neoarchean collisional orogeny. *Precambrian Research* 155,
 1253 159–203.

1254 Nutman, A.P., Friend, C.R.L., 2009. New 1:20,000 scale geological maps, synthesis and history
 1255 of investigation of the Isua supracrustal belt and adjacent orthogneisses, southern West
 1256 Greenland: A glimpse of Eoarchean crust formation and orogeny. *Precambrian Research* 172,
 1257 189–211.

1258 Nutman, A.P., Friend, C.R.L., Baadsgaard, H., McGregor, V.R., 1989. Evolution and assembly
 1259 of Archean gneiss terranes in the Godthåbsfjord region, southern West Greenland: structural,
 1260 metamorphic and isotopic evidence. *Tectonics* 8, 573–589.

1261 Nutman, A.P., Garde, A.A., 1989. Fluid control on emplacement of sialic magmas during
 1262 Archean crustal accretion. In: Bridgwater, D., (Ed.), *Fluid Movements – Element Transport*
 1263 *and the Composition of the Deep Crust*. Kluwer, Dordrecht, pp. 235–243.

1264 Nutman, A.P., McGregor, V.R., Friend, C.R.L., Bennett, V.C., Kinny, P.D., 1996. The Itsaq
 1265 Gneiss Complex of southern West Greenland; the world's most extensive record of early
 1266 crustal evolution. *Precambrian Research* 78, 1–39.

1267 Nutman, A.P., Friend, C.R.L., Paxton, S., 2009. Detrital zircon sedimentary provenance ages for
 1268 the Eoarchean Isua supracrustal belt southern West Greenland: Juxtaposition of a ca. 3700 Ma
 1269 juvenile arc assemblage against an older complex with 3920-3800 Ma components.
 1270 *Precambrian Research* 172, 212–233.

1271 Nutman, A.P., Friend, C.R.L., Bennett, V.C., 2002. Evidence for 3650-3600 Ma assembly of the
 1272 northern end of the Itsaq Gneiss Complex, Greenland: Implication for early Archean
 1273 tectonics. *Tectonics* 10.1029/2000TC001203.

1274 Nutman, A.P., Bennett, V.C., Friend, C.R.L., McGregor, V.R., 2000. The early Archean Itsaq
 1275 Gneissic Complex of southern West Greenland: the importance of field observations in
 1276 interpreting age and isotopic constraints for early terrestrial evolution. *Geochimica et*
 1277 *Cosmochimica Acta* 64, 3035–3060.

1278 Nutman, A.P., Bennett, V.C., Friend, C.R.L., Hidaka, H., Yi, K., Lee, S.R., Kamiichi, T., 2013.
 1279 The Itsaq Gneiss Complex of Greenland: Episodic 3900 to 3660 Ma juvenile crust formation
 1280 and recycling in the 3660–3600 Ma Isukasian orogeny. *American Journal of Science* 313,
 1281 877–911.

1282 Nutman, A.P., Friend, C.R.L., Barker, S.L.L., McGregor, V.R., 2004. Inventory and assessment
 1283 of Paleoarchean terrains and detrital zircons in southern West Greenland. *Precambrian*
 1284 *Research* 135, 281–314.

1285 Nutman, A.P., Kalsbeek, K., 1994. A minimum age of 2944 ± 7 Ma for the Tâtoq Group, South-
 1286 West Greenland. *Bulletin Grønlands Geologiske Undersøgelse* 161, 35–38.

1287 O’Neil, J., Francis, D., Carlson, R.W., 2011. Implications of the Nuvvuagittuq greenstone belt
 1288 for the formation of Earth’s early crust. *Journal of Petrology* 52, 985–1009.

- 1289 Ordóñez-Calderón, J.C., Polat, A., Fryer, B., Appel, P.W.U., van Gool, J.A.M., Dilek, Y.,
 1290 Gagnon, J.E., 2009. Geochemistry and geodynamic origin of Mesoarchean oceanic crust in
 1291 the Ujarassuit and Ivisaartoq greenstone belts, SW Greenland. *Lithos* 113, 133–157.
- 1292 Ordóñez-Calderón, J.C., Polat, A., Fryer, B.J., Gagnon, J.E., 2011. Field and geochemical
 1293 characteristics of Mesoarchean to Neoarchean volcanic rocks in the Storø greenstone belt, SW
 1294 Greenland: Evidence for accretion of intra-oceanic volcanic arcs. *Precambrian Research* 184,
 1295 24–42.
- 1296 Oreskes, N., 2003. *Plate Tectonics – An Insider’s History of the Modern Theory of the Earth*.
 1297 Westview Press, Colorado, 424 pp.
- 1298 Østergaard, C., van Gool, J.A.M., 2007. Assessment of gold mineralization on Storø,
 1299 Godthåbsfjord, southern West Greenland. *Danmarks Og Grønlands Geologiske Undersøgelse*
 1300 *Rapport 2007/78*, 20 pp.
- 1301 Owens, B.E., Dymek, R.F., 1997. Comparative petrology of Archean anorthosites in amphibolite
 1302 and granulite facies terranes, SW Greenland. *Contributions to Mineralogy and Petrology* 128,
 1303 371–384.
- 1304 Passchier, C.W., Myers, J.S., Kroner, A., 1990. *Field Geology of High-Grade Gneiss Terrains*,
 1305 Springer-Verlag, Berlin, 159 pp.
- 1306 Percival, J.A., Sanborn-Barrie, M., Skulski, T., Stott, G.M., Helmstaedt, H., White, D.J., 2006.
 1307 Tectonic evolution of the western Superior Province from NATMAP and Lithoprobe
 1308 studies. *Canadian Journal of Earth Sciences* 43, 1085–1117.
- 1309 Percival, J.A., Skulski, T., Sanborn-Barrie, M., Stott, G.M., Leclair, A.D., Corkery, M.T., Boily,
 1310 M., 2012. Geology and Tectonic Evolution of the Superior Province, Canada in: Percival,

1311 J.A., Cook, F.A., Clowes, R.M., (Eds.), Tectonic Styles in Canada: The LITHOPROBE
 1312 Perspective. Geological Association of Canada Special Paper 49, pp. 321–378.
 1313 Petersen, J.S., 1992. Nuuluk-Iterlak gold and massive-sulfide project, Taartoq Archaean
 1314 greenstone belt, SW Greenland. (Field report, Nunaoil A/S, 164 pp).
 1315 Pidgeon, R.T., Kalsbeek, F., 1978. Dating of igneous and metamorphic events in the Fiskenæsset
 1316 region of southern West Greenland. Canadian Journal of Earth Sciences 15, 2021–2025.
 1317 Polat, A., 2014. John Tuzo Wilson: a Canadian who revolutionized Earth Sciences. Canadian
 1318 Journal of Earth Sciences 51, v–viii.
 1319 Polat, A., 2012. Growth of Archean continental crust in oceanic island arcs. Geology 40, 383–
 1320 384.
 1321 Polat, A., Dziggel, A., 2011. Summary of field work in the Tartoq Group in 2010, pp. 148–158.
 1322 Geological Survey of Denmark and Greenland, Ministry of Climate and Energy Report
 1323 2011/114.
 1324 Polat, A., Frei, R., 2005. The origin of early Archean banded iron formations and of continental
 1325 crust, Isua, southern West Greenland. Precambrian Research 138, 151–175.
 1326 Polat, A., Frei, R., Fryer, B., Appel, P.W.U., 2009a. The origin of geochemical trends and
 1327 Eoarchean (ca. 3700 Ma) zircons in Mesoarchean (ca. 3075 Ma) ocelli-hosting pillow basalts,
 1328 Ivisaartoq greenstone belt, SW Greenland: evidence for crustal contamination versus crustal
 1329 recycling. Chemical Geology 268, 248–271.
 1330 Polat, A., Appel, P.W.U., Fryer, B., Windley, B., Frei, R., Samson, I.M., Huang, H., 2009b.
 1331 Trace element systematics of the Neoarchean Fiskenæsset anorthosite complex and associated
 1332 meta-volcanic rocks, SW Greenland: Evidence for a magmatic arc origin. Precambrian
 1333 Research 175, 87–115.

1334 Polat, A., Appel, P.W.U., Fryer, B., 2011a. An overview of the geochemistry of Eoarchean to
 1335 Mesoarchean ultramafic to mafic volcanic rocks, SW Greenland: Implications for mantle
 1336 depletion and petrogenetic processes at subduction zones in the early Earth. *Gondwana*
 1337 *Research* 20, 255–283.

1338 Polat, A., Appel, P.W.U., Frei, R., Pan, Y., Dilek, Y., Ordóñez-Calderón, J.C., Fryer, B., Hollis,
 1339 J.A., Raith, J.G., 2007. Field and geochemical characteristics of the Mesoarchean (~3075 Ma)
 1340 Ivisartoq greenstone belt, southern West Greenland: Evidence for seafloor hydrothermal
 1341 alteration in a supra-subduction oceanic crust. *Gondwana Research* 11, 69–91.

1342 Polat, A., Frei, R., Appel, P.W.U., Dilek, Y., Fryer, B., Ordóñez-Calderón, J.C., Yang, Z., 2008.
 1343 The origin and compositions of Mesoarchean oceanic crust: Evidence from the 3075 Ma
 1344 Ivisartoq greenstone belt, SW Greenland. *Lithos* 100, 293–321.

1345 Polat, A., Fryer, B., Appel, P.W.U., Kalvig, P., Kerrich, R., Dilek, Y., Yang, Z., 2011b.
 1346 Geochemistry of anorthositic differentiated sills in the Archean (~2970 Ma) Fiskensæset
 1347 Complex, SW Greenland: Implications for parental magma compositions, geodynamic
 1348 setting, and secular heat flow in arcs. *Lithos* 123, 50–72.

1349 Polat, A., Fryer, B., Samson, I.M., Weisener, C., Appel, P.W.U., Frei, R., Windley, B.F., 2012.
 1350 Geochemistry of ultramafic rocks and hornblende veins in the Fiskensæset layered
 1351 anorthosite complex, SW Greenland: Evidence for hydrous upper mantle in the Archean.
 1352 *Precambrian Research* 214–215, 124–153.

1353 Polat, A., Hofmann, A.W., 2003. Alteration and geochemical patterns in the 3.7–3.8 Ga Isua
 1354 greenstone belt, West Greenland. *Precambrian Research* 126, 197–218.

1355 Polat, A., Hofmann, A.W., Rosing, M., 2002. Boninite-like volcanic rocks in the 3.7 – 3.8 Ga
 1356 Isua greenstone belt, West Greenland: Geochemical evidence for intra-oceanic subduction
 1357 zone processes in the early Earth. *Chemical Geology* 184, 231–254.

1358 Polat, A., Frei, R., Scherstén, A., Appel, P. W.U., 2010. New age (ca. 2970 Ma), mantle source
 1359 composition and geodynamic constraints on the Archean Fiskensæset anorthosite complex,
 1360 SW Greenland. *Chemical Geology* 277, 1–20.

1361 Polat, A., Longstaffe, F.J., 2014. A juvenile oceanic island arc origin for the Archean (ca. 2.97
 1362 Ga) Fiskensæset Anorthosite Complex, southwestern Greenland: Evidence from oxygen
 1363 isotopes. *Earth and Planetary Science Letters* 396, 252–266.

1364 Polat, A., Kerrich, R., 2006. Reading the Geochemical Fingerprints of Archean Hot Subduction
 1365 Volcanic Rocks: Evidence for Accretion and Crustal Recycling in a Mobile Tectonic Regime.
 1366 AGU Geophysical Monograph Series 164, 189–213.

1367 Polat, A., Kerrich, R., Windley, B.F., 2009c. Archean crustal growth processes in the southern
 1368 Superior Province and southern West Greenland: geodynamic and magmatic constraints. In:
 1369 Cawood, P., Kröner, A., (Eds.), *Accretionary Orogens in Space and Time*, Geological Society
 1370 of London, Special Publication 318, 155–191.

1371 Ratschbacher, L., Franz, L., Enkelmann, E., Jonckheere, R., Pörschke, A., Hacker, B.R., Dong,
 1372 S.W., Zhang, Y.Q., 2006. The Sino-Korean Yangtze suture, the Huwan detachment, and the
 1373 Paleozoic-Tertiary exhumation of (ultra)high-pressure rocks along the Tongbai-Xinxian-
 1374 Dabie Mountains. In: Hacker, B.R., McClelland, W.C., Liou, J.G., (Eds.), *Ultrahigh-pressure
 1375 Metamorphism: Deep Continental Subduction*. Geological Society of America Special Paper,
 1376 vol. 403, pp. 45–75.

- 1377 Riciputi, L.R., Valley, J.W., McGregor, V.R., 1990. Conditions of Archean granulite
1378 metamorphism in the Godthåb-Fiskenæsset region, southern West Greenland. *Journal of*
1379 *Metamorphic Geology* 8, 171–190.
- 1380 Robin, C.M.I., Bailey, R.C., 2009. Simultaneous generation of Archean crust and subcratonic
1381 roots by vertical tectonics. *Geology* 37, 523–526.
- 1382 Rollinson, H, Claire Reid, C., Windley, B.F., 2010. Chromitites from the Fiskenæsset
1383 anorthositic complex, West Greenland: clues to late Archaean mantle processes. In: Kusky,
1384 T.M., Zhai, M., Xiao, W. (Eds.), *The Evolving Continents: Understanding Processes of*
1385 *Continental Growth*. Geological Society of London, Special Publications, 338, 197–212.
- 1386 Rosing, M.T., Nutman, A.P., Løfqvist, L., 2001. A new fragment of the early earth crust: the
1387 Aasivik terrane of West Greenland. *Precambrian Research* 105, 115–128.
- 1388 Santosh, M., Shaji, E., Tsunogae, T., Ram Mohan, M., Satyanarayanan, M., Horie, K., 2013.
1389 Suprasubduction zone ophiolite from Agali hill: Petrology, zircon SHRIMP U–Pb
1390 geochronology, geochemistry and implications for Neoproterozoic plate tectonics in southern
1391 India. *Precambrian Research* 231, 301–324.
- 1392 Saleeby, J.A., 1992. Age and tectonic setting of the Duke Island ultramafic intrusion, southeast
1393 Alaska. *Canadian Journal of Earth Sciences* 29, 506–522.
- 1394 Savage, B., 2012. Seismic constraints on the water flux delivered to the deep Earth by
1395 subduction. *Geology* 40, 235–238.
- 1396 Sawyer, E.W., 2008. *Atlas of migmatites*. Canadian Mineralogical Association Special
1397 Publication 9, NRC Research Press, Ottawa, pp 371.
- 1398 Schaefer, B.F., Turner, S., Parkinson, I., Rogers, N., Hawkesworth, C., 2002. Evidence for
1399 recycled Archean oceanic mantle lithosphere in the Azores plume. *Nature* 420, 304–307.

- 1400 Scherstén, A., Szilas, K., Creaser, R.A., van Gool, J.A.M., Næraa, T., Østergaard, C., 2012. Re-
 1401 Os and U–Pb constraints on gold mineralisation events in the Meso- to Neoarchaeon Storø
 1402 greenstone belt, Storø, southern West Greenland. *Precambrian Research* 200–203, 149–162.
- 1403 Schumacher, J.C., van Hinsberg, V.J., Keulen, N., 2011. Metamorphism in supracrustal and
 1404 ultramafic rocks in southern West Greenland and South-West Greenland 64–61.5 °N.
 1405 Danmarks og Grønlands Geologiske Undersøgelse Rapport 2011/06, 29 pp.
- 1406 Şengör, A.M.C. 1990. Plate Tectonics and orogenic research after 25 years: A Tethyan
 1407 perspective. *Earth Science Reviews* 27, 1–201.
- 1408 Şengör, A.M.C., Natal'in, B.A., Burtman, V.S., 1993. Evolution of the Altaid tectonic collage
 1409 and Phanerozoic crustal growth in Eurasia. *Nature* 364, 299–307.
- 1410 Şengör, A.M.C., Natal'in, B.A., 1996. Turkic-type orogeny and its rôle in the making of the
 1411 continental crust. *Annual Reviews of Earth Planetary Sciences* 24, 263–337.
- 1412 Şengör, A.M.C., Natal'in, B. A., 2004. Phanerozoic analogues of Archaean oceanic basement
 1413 fragments: Altaid ophiolites and ophiirags. In: Kusky T.M. (Ed.), *Precambrian Ophiolites and*
 1414 *Related Rocks, Developments in Precambrian Geology*, Vol. 13 (K.C. Condie, Series Editor),
 1415 Elsevier B.V., Amsterdam, pp. 675-726.
- 1416 Şengör, A.M.C., Natal'in, B.A., Sunal, G., van der Voo, R., 2014. A new look at the Altaids: A
 1417 superorogenic complex in Northern and Central Asia as a factory of continental crust. Part I:
 1418 Geological data compilation (exclusive of palaeomagnetic observations). *Austrian Journal of*
 1419 *Earth Sciences* 107, 169–232.
- 1420 Sleep, N.H., 1992. Archean plate tectonics: what can be learned from continental geology?
 1421 *Canadian Journal of Earth Sciences* 29, 2066–2071.

- 1422 Sobolev, A.V., Hofmann, A.W., Nikosian, I.K., 2000. Recycled oceanic crust observed in ‘ghost
1423 plagioclase’ within the source of Mauna Loa lavas. *Nature* 404, 986-990.
- 1424 Souders, A.K., Sylvester, P.J., Myers, J.S., 2013. Mantle and crustal sources of Archean
1425 anorthosite: a combined in situ isotopic study of Pb–Pb in plagioclase and Lu–Hf in zircon.
1426 *Contributions to Mineralogy and Petrology* 165, 1–24.
- 1427 Steenfelt, A., Garde, A.A., Moyen, J.-F., 2005. Mantle wedge involvement in the petrogenesis of
1428 Archaean grey gneisses in West Greenland. *Lithos* 79, 207–228.
- 1429 Stern, R.J., 2005. Evidence from ophiolites, blueschists, and ultrahigh-pressure metamorphic
1430 terranes that the modern episode of subduction tectonics began in Neoproterozoic time.
1431 *Geology* 33, 557–560.
- 1432 Stott, G. M., 1997. The Superior Province, Canada. In: de Wit, Ashwal, L.D., (Eds.), *Tectonic
1433 Evolution of Greenstone Belts*. Oxford Monographs on Geology and Geophysics 35,
1434 Clarendon Press, Oxford, pp. 480–507.
- 1435 Szilas, K., Garde, A.A., 2013. Mesoarchaean aluminous rocks at Storø, southern West
1436 Greenland: New age data and evidence of premetamorphic seafloor weathering of basalts.
1437 *Chemical Geology* 354, 124–138.
- 1438 Szilas, K., van Hinsberg, J., Creaser, R., Kisters, A.F.M., 2014. The geochemical composition of
1439 serpentinites in the Mesoarchaean Tartoq Group, SW Greenland: Harzburgitic cumulates or
1440 melt modified mantle? *Lithos* 198–199, 103–116.
- 1441 Szilas, K., Hoffmann, J.E., Scherstén, A., Rosing, M.T., Windley, B.F., Kokfelt, T.F., Keulen,
1442 N., van Hinsberg, V.J., Næraa, T., Frei, R., Carsten Münker, C., 2012a. Complex calc-
1443 alkaline volcanism recorded in Mesoarchaean supracrustal belts north of Frederikshåb Isblink,

1444 southern West Greenland: Implications for subduction zone processes in the early Earth.
 1445 Precambrian Research 208–211, 90– 123

1446 Szilas, K., Næraa, T., Scherstén, A., Stendal, H., Frei, R., van Hinsberg, V. J., Kokfelt, T.F.,
 1447 Rosing, M. T. 2012b. Origin of Mesoarchaeoan arc-related rocks with boninite/komatiite
 1448 affinities from southern West Greenland. *Lithos* 144, 24–39.

1449 Szilas, K., Van Hinsberg, V.J., Kisters, A.F.M., Hoffmann, J.E., Windley, B.F., Kokfelt, T.F.,
 1450 Scherstén, A., Frei, R., Rosing, M.T., Münker, C., 2013a. Remnants of arc-related
 1451 Mesoarchean oceanic crust in the Tartoq Group of SW Greenland. *Gondwana Research* 23,
 1452 436–451.

1453 Szilas, K., Hoffmann, J.E., Scherstén, A., Kokfelt, T.F., Münker, C., 2013b. Archean andesite
 1454 petrogenesis: Insights from the Grædefjord Supracrustal Belt, southern West Greenland.
 1455 Precambrian Research 236, 1–15.

1456 Szilas, K., van Gool, J. A., Scherstén, A., Frei, R., 2014. The Neoarchaeoan Storø Supracrustal
 1457 Belt, Nuuk region, southern West Greenland: An arc-related basin with continent-derived
 1458 sedimentation. *Precambrian Research* 247, 208–222.

1459 Tappe, S., Smart, K.A., Pearson, D.G., Steenfelt, A., Simonetti, A., 2011. Craton formation in
 1460 Late Archean subduction zones revealed by first Greenland eclogites. *Geology* 39, 1103–
 1461 1106.

1462 Thébaud, N., Rey, P.F., 2013. Archean gravity-driven tectonics on hot and flooded continents:
 1463 Controls on long-lived mineralised hydrothermal systems away from continental margins.
 1464 Precambrian Research 229, 93–104.

1465 Turner, S., Rushmer, T., Reagan, M., Moyen, J.-F., 2014. Heading down early on? Start of
 1466 subduction on Earth. *Geology* 42, 139–142.

1467 van Gool, J.A.M., Scherstén, A., Østergaard, C., Næraa, T., 2007. Geological setting of the Storø
 1468 gold prospect, Godthåbsfjord region, southern West Greenland. Danmarks Og Grønlands
 1469 Geologiske Undersøgelse Rapport 2007/83, 158 pp.

1470 Wager, L. R., Brown, G. M., 1968. Layered Igneous Rocks. Edinburgh, Oliver and Boyd, Ltd.

1471 Wang, L., Kusky, T.M., Li, S., 2010. Structural geometry of an exhumed UHP terrane in the
 1472 eastern Sulu Orogen, China: Implications for continental collisional processes. Journal of
 1473 Structural Geology 32, 423–444.

1474 Wang, L. Kusky, T.M., Polat, A., Wang, S., Jiang, X., Zong, K., Wang, J., Deng, H., Fu, J.,
 1475 2014. Partial melting of deeply subducted eclogite from the Sulu orogen in China. Nature
 1476 Communications, 5:5604 | DOI: 10.1038/ncomms6604.

1477 Wang, J.P., Kusky, T.M., Polat, A., Wang, L. Deng, H., Wang, S., 2013. A late Archean tectonic
 1478 mélange in the Central Orogenic Belt, North China Craton. Tectonophysics 608, 929–946.

1479 Wedepohl, K.H., Heinrichs, H., Bridgwater, D., 1991. Chemical characteristics and genesis of
 1480 the quartzo-feldspathic rocks in the Archean crust of Greenland. Contributions to Mineralogy
 1481 and Petrology 107, 163–179.

1482 Weaver, B.L., Tarney, J., Windley, B., 1981. Geochemistry and petrogenesis of the Fiskensæst
 1483 anorthosites complex, southern West Greenland: nature and parent magma. Geochimica et
 1484 Cosmochimica Acta 45, 711–725.

1485 Weaver, B.L., Tarney, J., Windley, B., Leake, B.E., 1982. Geochemistry and petrogenesis of
 1486 Archean metavolcanic amphibolites from Fiskensæst, S.W. Greenland. Geochimica et
 1487 Cosmochimica Acta 46, 2203–2215.

1488 Wells, P.R.A., 1979. Chemical and thermal evolution of Archaean sialic crust, southern West
 1489 Greenland. Journal of Petrology 20, 187–226.

1490 Wells, P.R.A., 1981. Accretion of continental crust: thermal and geochemical consequences.
1491 Philosophical Transactions of the Royal Society (London) A301, 347–357.

1492 Windley, B.F., 1968. New Field relations from the early Precambrian of West Greenland.
1493 Grønlands Rapport Grønlands Geologiske Undersøgelse 15, 27–31.

1494 Windley, B.F., 1993. Uniformitarianism today: plate tectonics is the key to the past. Journal of
1495 Geological Society, London, 150, 7–19.

1496 Windley, B.F., Garde, A.A., 2009. Arc-generated blocks with crustal sections in the North
1497 Atlantic craton of West Greenland: new mechanism of crustal growth in the Archean with
1498 modern analogues. Earth Science Reviews 93, 1–30.

1499 Windley, B.F., Smith, J.V., 1974. The Fiskensæset Complex, West Greenland, part 2. General
1500 Mineral Chemistry from Qeqertarsuatsiaq. Grønlands Geologiske Undersøgelse Bulletin 108,
1501 54 pp.

1502 Windley, B.F., Smith, J.V., 1976. Archaean high-grade complexes and modern continental
1503 margins. Nature 260, 671–675.

1504 Windley, B.F., Bishop, F.C., Smith, J.V., 1981. Metamorphosed layered igneous complexes in
1505 Archean granulite–gneiss belts. Annual Reviews Earth and Planetary Sciences 9, 175–198.

1506 Yoshida, D., Hirajima, T., Ishiwatari, A., 2004. Pressure-temperature path recorded in the
1507 Yangkou garnet-peridotite, in Su-Lu UHP metamorphic belt, eastern China. Journal of
1508 Petrology 45, 1125–1145.

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FIGURE CAPTIONS

Fig. 1. Simplified geological map of the Archean craton of West Greenland, showing the locations of the Isua, Ivisaartoq-Ujarassuit, Qussuk, Bjørneøen, Storø, Grædefjord, Ravns Storø, Bjørnesund, Akuliaq Peninsula, and Tartoq supracrustal belts, the Fiskenæsset anorthositic complex, and Maniitsoq structure (modified after Escher and Pulvertaft, 1995).

Fig. 2. Simplified geological map of the Fiskefjord and Napassoq regions, displaying a variety of fold interference patterns (modified from Geological map of sheet 2 Fredrikshåb Isblink–Søndre – Strømfjord, Geological Survey of Greenland). Mesoarchean homogenized gneisses occur within the Maniitsoq impact structure (see Garde et al., 2014).

Fig. 3. Simplified geological map of the Godthåbsfjord and Ameralik regions, displaying a variety of fold interference patterns (modified from Geological map of sheet 2 Fredrikshåb Isblink–Søndre – Strømfjord, Geological Survey of Greenland).

Fig. 4. Field photographs of structures at contacts between the supracrustal belts and the bordering TTG gneisses, and at contacts between the Fiskenæsset anorthositic complex and the bordering TTG gneisses in the Archean craton of West Greenland, indicating that the contacts are tectonic and characterized by mylonitic shear zones. Photographs (a-c) are from contact between the Akuliaq supracrustal belt and the bordering TTG gneisses; photograph (d) is from contact between the Ivisaartoq-Ujarassuit supracrustal belt and the bordering TTG gneisses; and photographs (e) and (f) are from contact between the Fiskenæsset anorthositic complex and the bordering TTG gneisses. Photograph (d) is from Polat et al. (2011a).

Fig. 5. Field photographs of the major lithologies in the Eoarchean Isua supracrustal belt, consistent with an intra-oceanic lithological assemblage. Photograph (a) is from Polat et al.

1535 (2009c), photograph (b) is from Polat and Frei (2005), and photographs (c), (d), (e) and (f) are
1536 from Hoffmann et al. (2010).

1537 Fig. 6. Field photographs of a shear zone (a), overturned asymmetric Z- and S-folds (b), and a
1538 thrust fault (c) in the Eoarchean Isua supracrustal belt.

1539 Fig. 7. Field photographs of the major rock types in the Mesoarchean Ivisartoq-Ujarassuit
1540 supracrustal belt, consistent with an intra-oceanic lithological assemblage. Photograph (a) is
1541 from Polat et al. (2007), photographs (b), (c) and (d) are from Polat et al. (2008), and
1542 photograph (e) is from Polat et al. (2011a).

1543 Fig. 8. Field photographs of the major rock types in the Neoarchean to Mesoarchean Storø
1544 supracrustal belt in the Godthåbsfjord region. Photographs (b) and (f) are from (Ordóñez-
1545 Calderón et al. (2011).

1546 Fig. 9. Field photographs of the major lithologies in the Mesoarchean Fiskensæset (a-c), Ravens
1547 Storø (d and e) and Bjørnesund (f) supracrustal belt. Photograph (a) is from Polat et al.
1548 (2009b).

1549 Fig. 10. Field photographs of the major rock types and structures in the Mesoarchean Tartok
1550 supracrustal belt. Photographs (d), (e) and (f) show the thrust faults and tectonic imbrication
1551 in the belt.

1552 Fig. 11. (a-b) Intrusion of a tonalite sheet along a thrust fault zone between two layers of
1553 anorthosite-leucogabbro at Sinarssuk in the Fiskensæset Complex. (c) A simplified cross-
1554 section of the Fiskensæset region through Majorqap qâva, relating the northern
1555 (Qeqertarssuatsiaq – Majorqap qâva – Sinarssuk) and southern (Kangârssuk – Qasse –
1556 Bjørnesund) belts (see Fig. 1); F₁ and F₂ represent the folds formed during first and second
1557 folding episodes (Modified from Myers, 1985).

Fig. 12. Field photographs of the major rock types in the Mesoarchean Fiskenæsset anorthosite complex. Photographs (a), (e) and (f) are from Polat et al. (2009b), photograph (b) is from Huang et al. (2012), photograph (c) from Polat et al. (2010), and photograph (d) is from Polat et al. (2011b).

Fig. 13. Field photographs from a shear zone between the Akuliaq supracrustal belt and the bordering TTG gneisses in the Akuliaq Peninsula of the Paamiut region. The patterns of these outcrop scale structures are similar to those developed on regional scales as shown in Figs. 2 and 3.

Fig. 14. Field photographs from the Fiskenæsset (a, b, c, e and f) and Ivisaartoq-Ujarassuit (d) regions showing the deformation and partial melting of amphibolites, and formation of TTG and granitic rocks.

Fig. 15. Field photographs from the Fiskenæsset region showing the deformation and partial melting of amphibolites, and formation of TTG and granitic rocks.

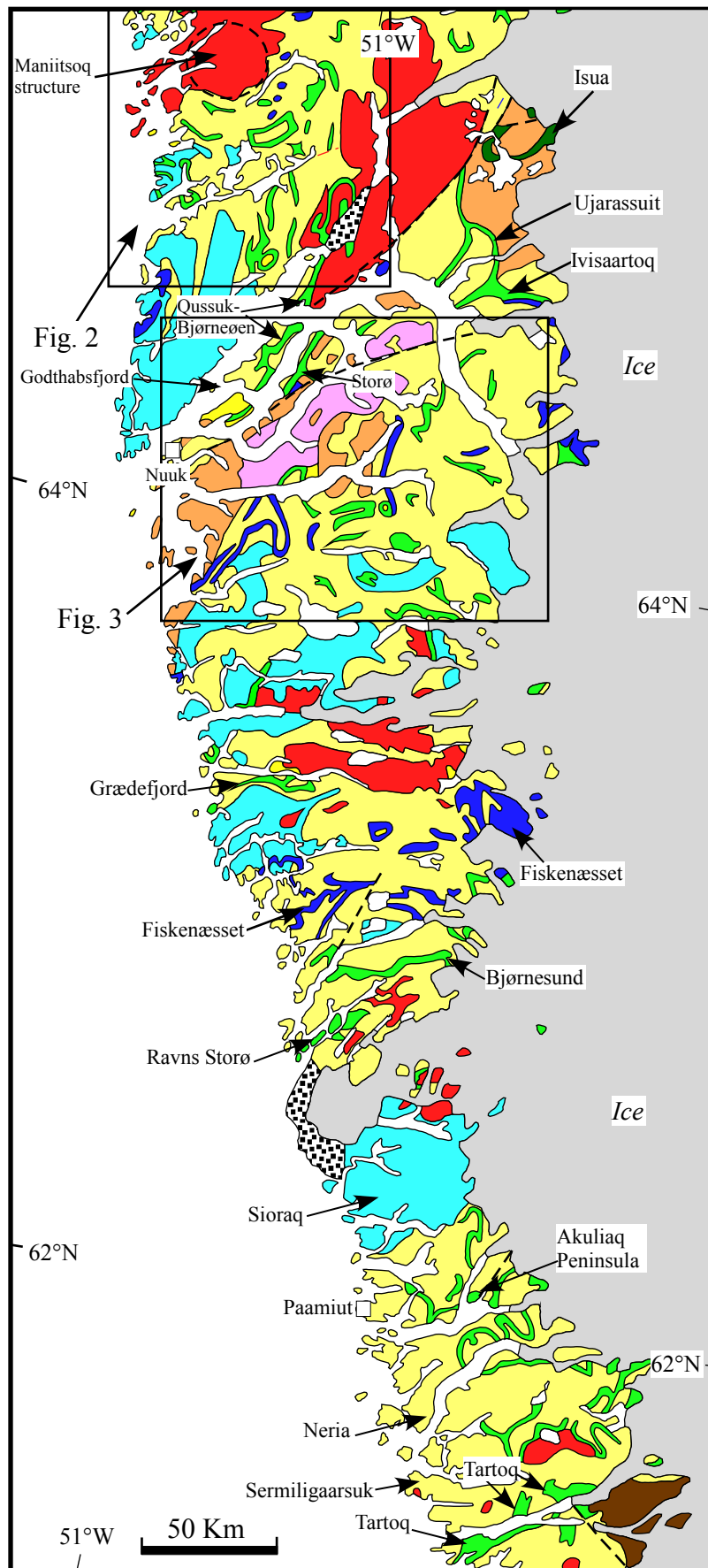
Fig. 16. A simple geodynamic model suggesting that some of the supracrustal belts (e.g., Isua, Ivisaartoq-Ujarassuit, Storø and Tartoq) in the Archean craton of West Greenland formed as accretionary complexes and oceanic island arc-forearcs (e.g., Fiskenæsset, Bjørnesund, Qussuk).

Fig. 17. A simple geodynamic model suggesting that TTGs in the Archean craton of West Greenland were generated through partial melting of amphibolites in thickened arcs, and partial melting of mantle wedge and subducted oceanic crust.












Fig. 18. Geological map of the Sulu ultrahigh-pressure (UHP) metamorphic belt (after Yoshida et al., 2004). Inset shows location of the Sulu Belt at the eastern end of the Qinling-Dabie orogen.

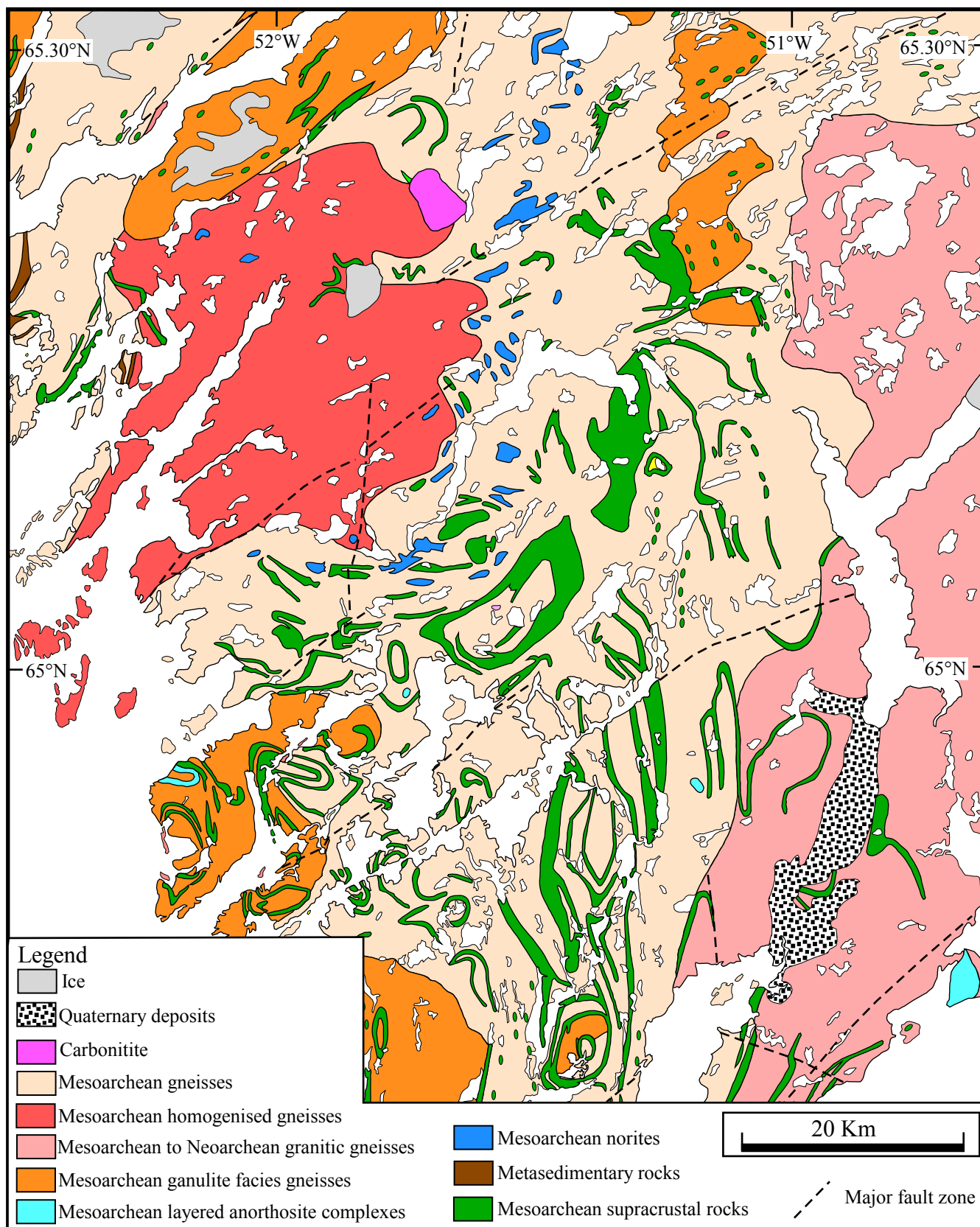
1581 Fig. 19. Structural map of the General's Hill outcrop in the Sulu orogenic belt, Yangkou Bay,
1582 eastern China (modified after Wang et al., 2014).

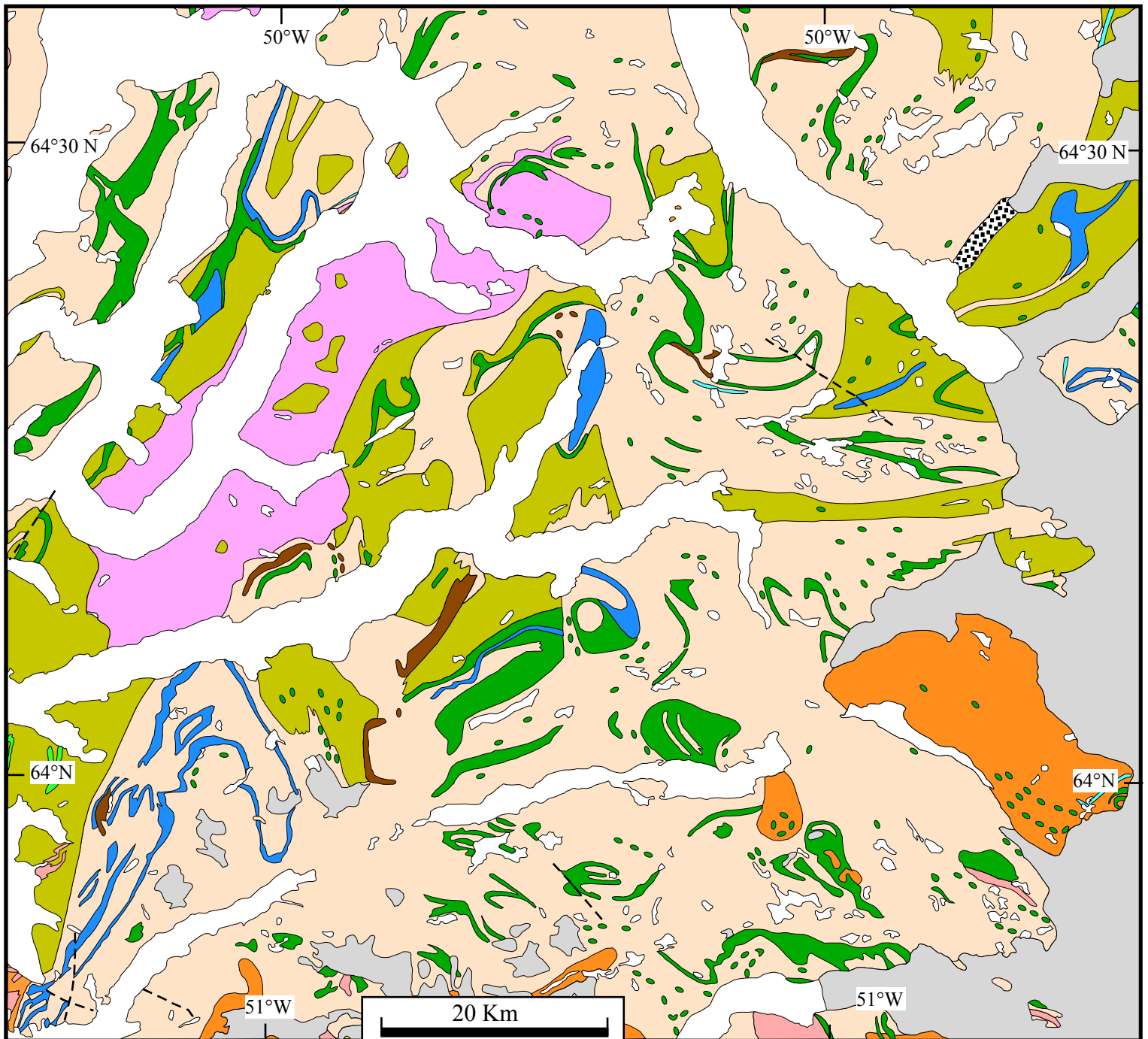
1583 Fig. 20. Field photographs from the General's Hill outcrop, showing the deformation and partial
1584 melting of eclogites and retrogressed eclogites (amphibolites), forming an eclogitic migmatite
1585 with the felsic rocks contributing to the formation of continental crust. Black and red colors
1586 represent the mafic rocks (eclogites and amphibolites) and light color shows the felsic
1587 (leucosome) rocks.















Legend

-  Quaternary deposits
-  Proterozoic supracrustal rocks
-  Neoproterozoic granites (Qôrquut granite)
-  Mesoproterozoic to Neoproterozoic granitic gneisses
-  Mesoproterozoic granulite facies gneisses
-  Mesoproterozoic gneisses
-  Mesoproterozoic layered anorthosite complexes
-  Mesoproterozoic supracrustal rocks
-  Eoproterozoic gneisses
-  Eoproterozoic supracrustal rocks
-  Major fault zone

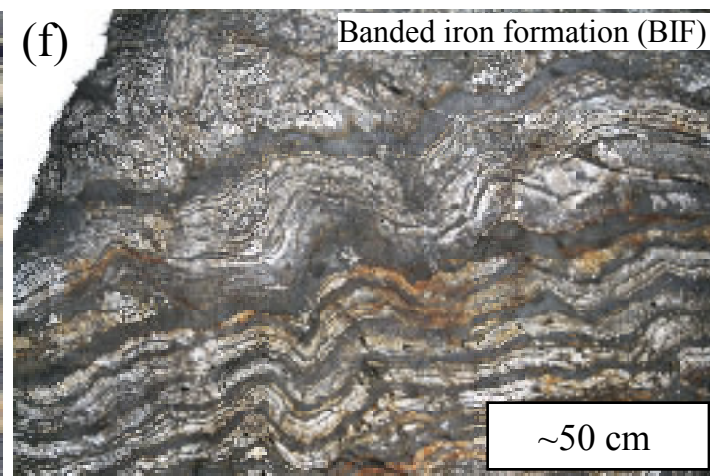
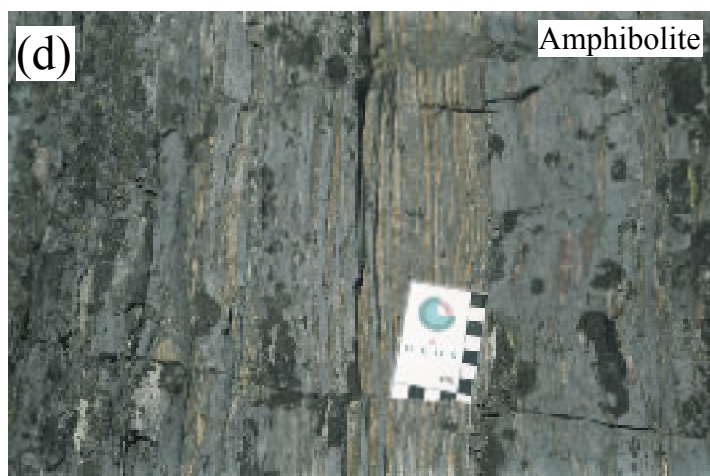
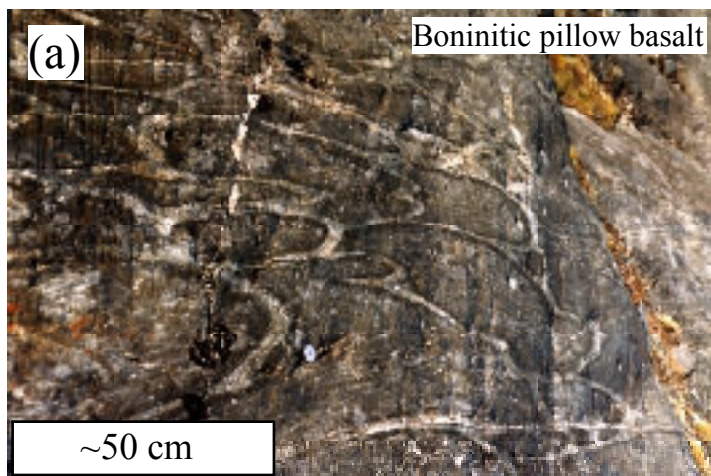


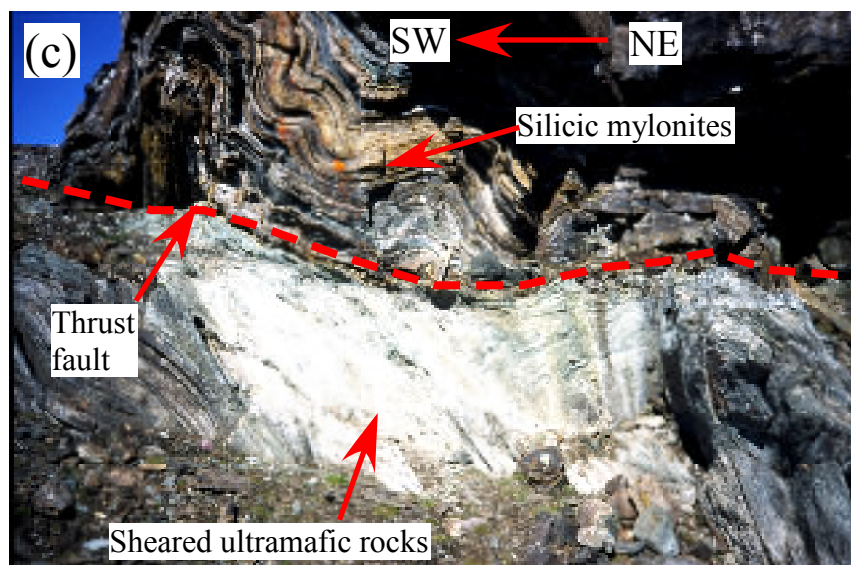
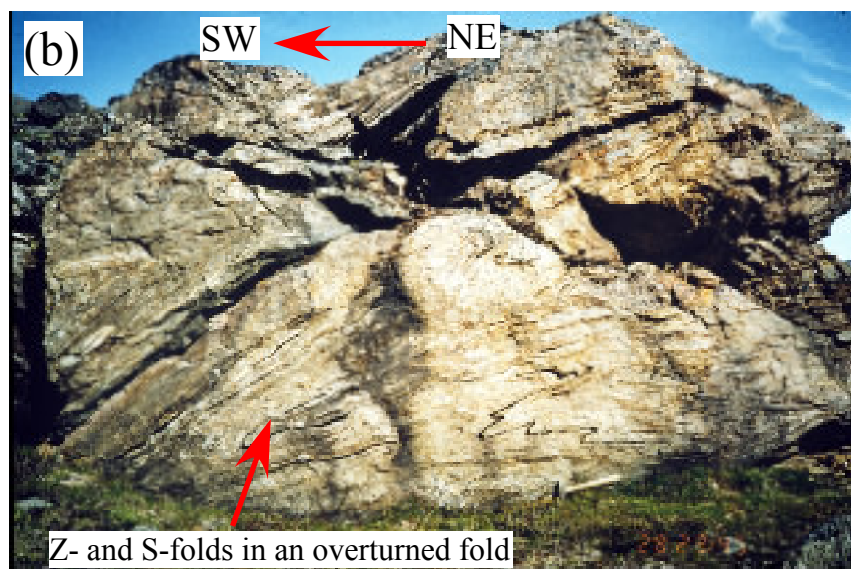


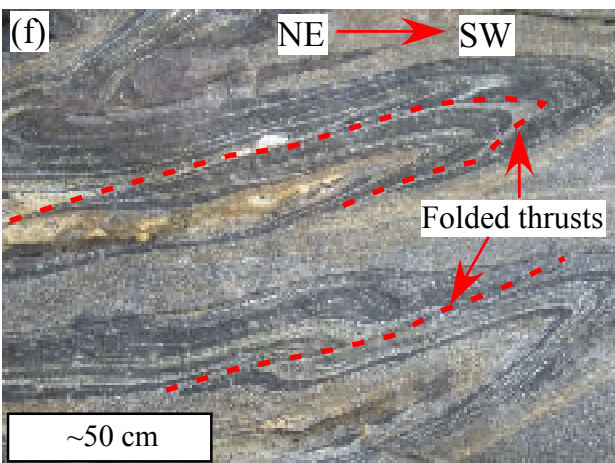
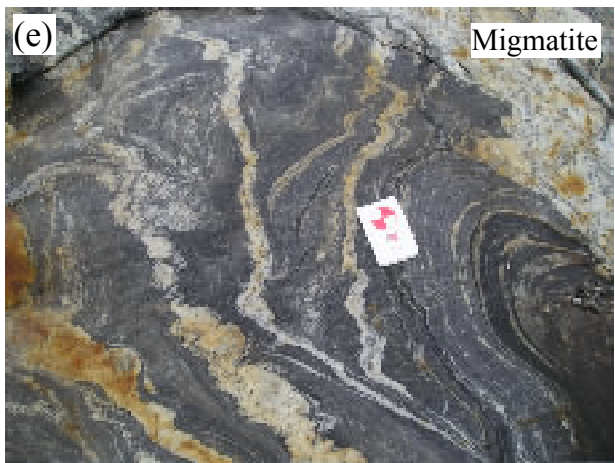
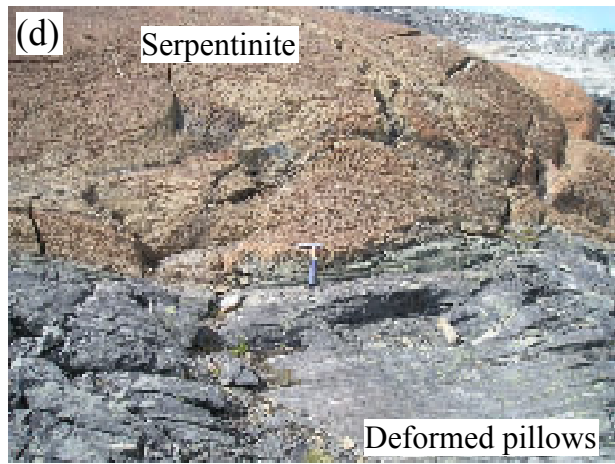
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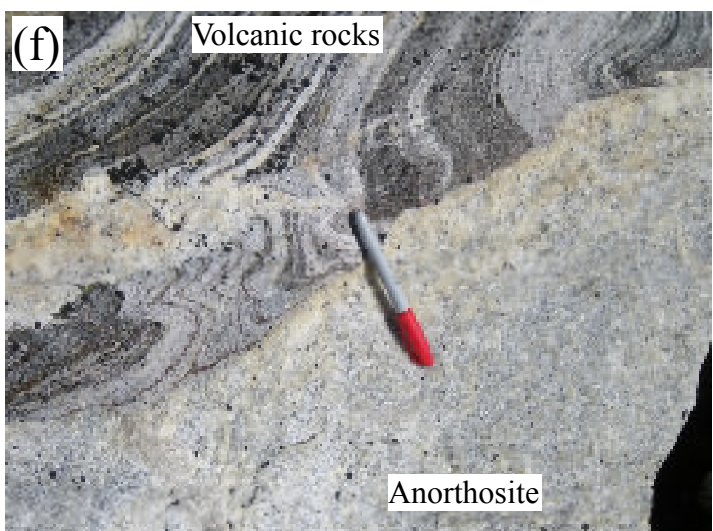
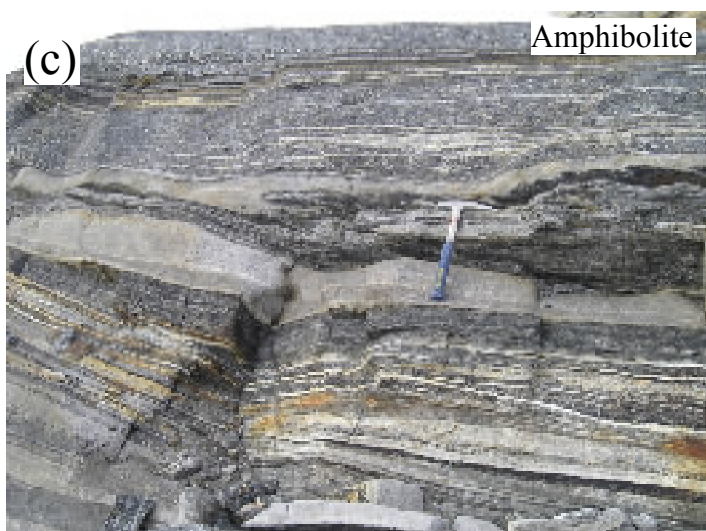
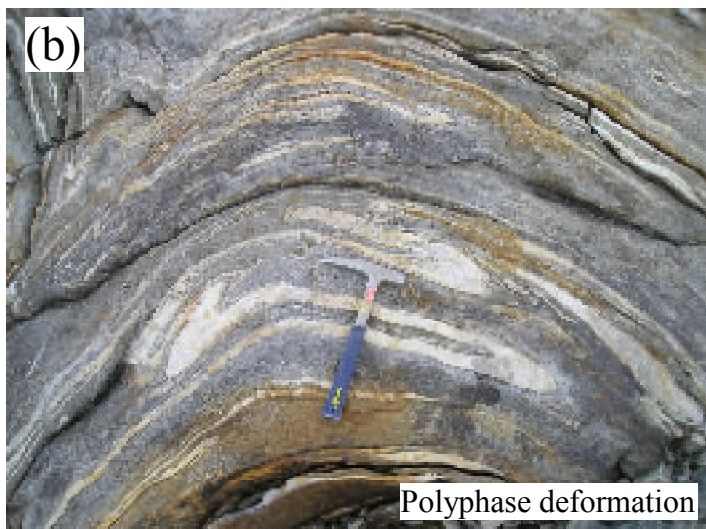
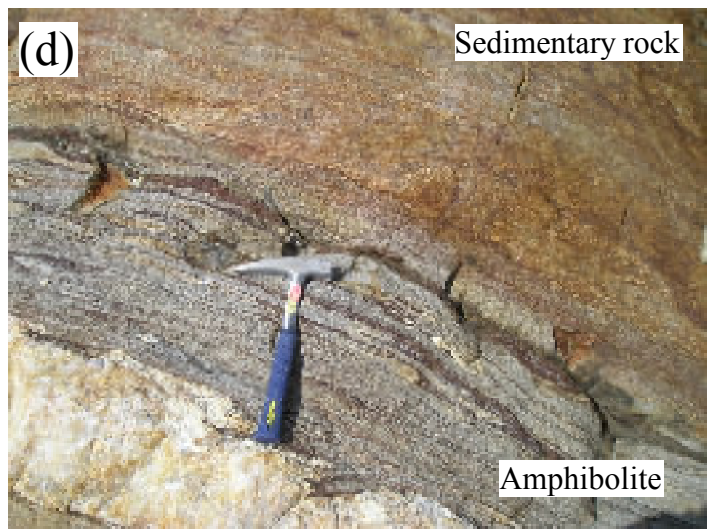
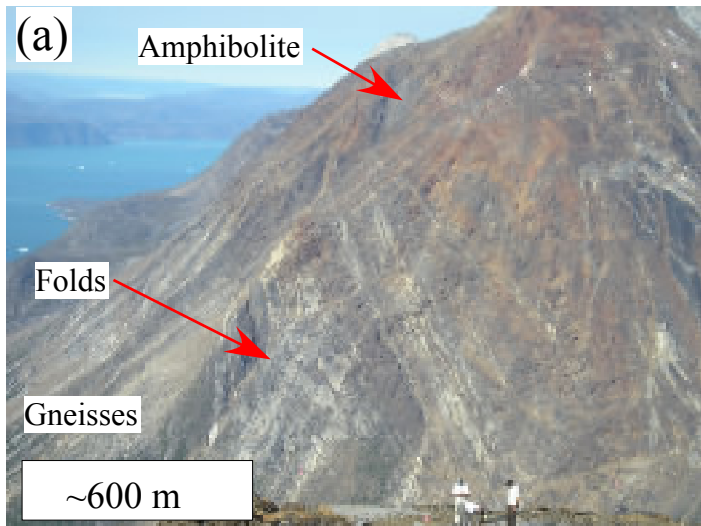
- | | |
|--|---|
|  Ice |  Mesoarchean layered anorthosite complexes |
|  Quaternary deposits |  Metasedimentary rocks |
|  Neoproterozoic granites (Qôrqut granite) |  Mesoarchean supracrustal rocks |
|  Mesoarchean to Neoproterozoic granitic gneisses |  Eoarchean gneisses |
|  Mesoarchean granulite facies gneisses |  Eoarchean supracrustal rocks |
|  Mesoarchean gneisses |  Major fault zone |

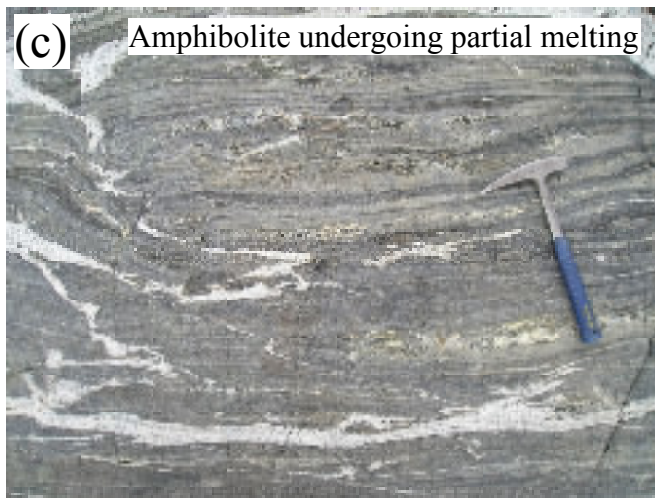
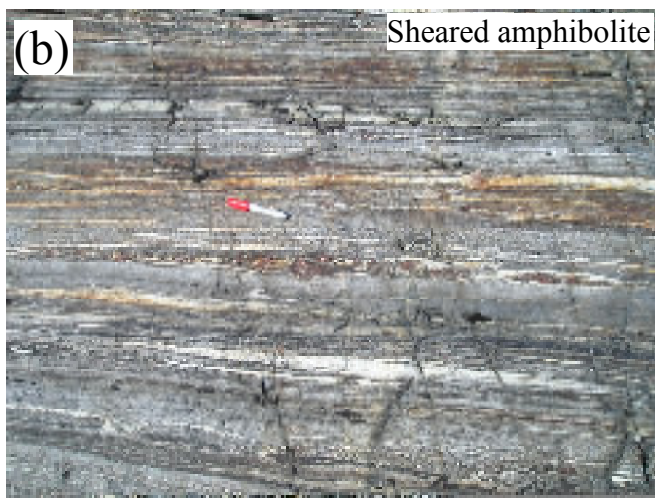
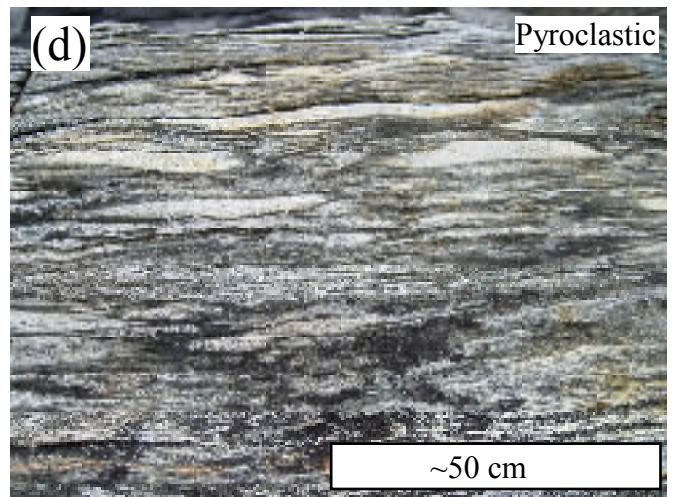
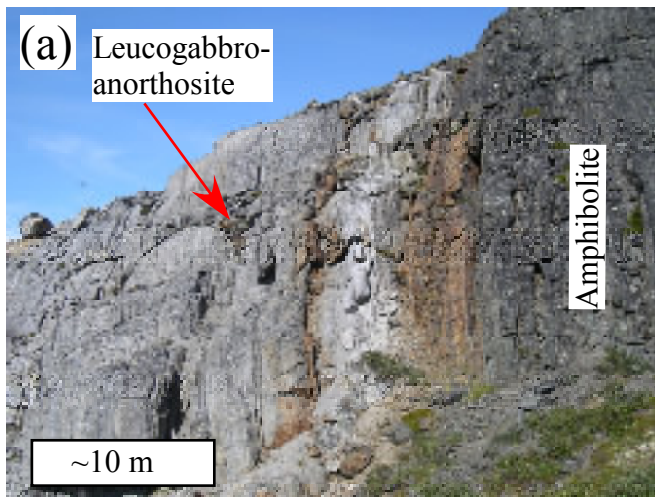


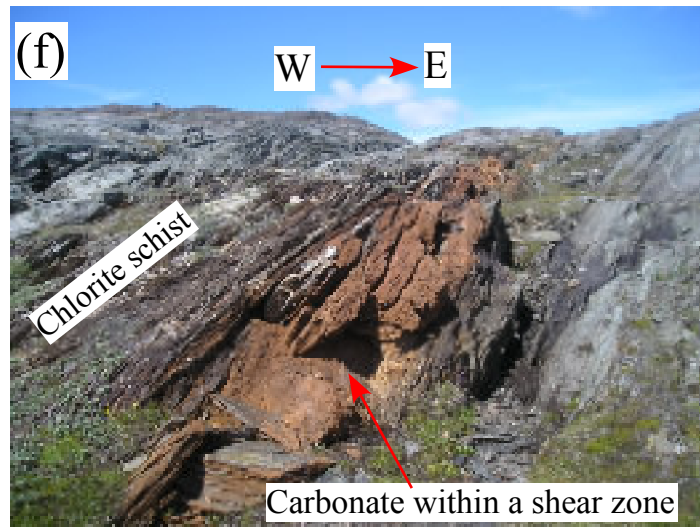
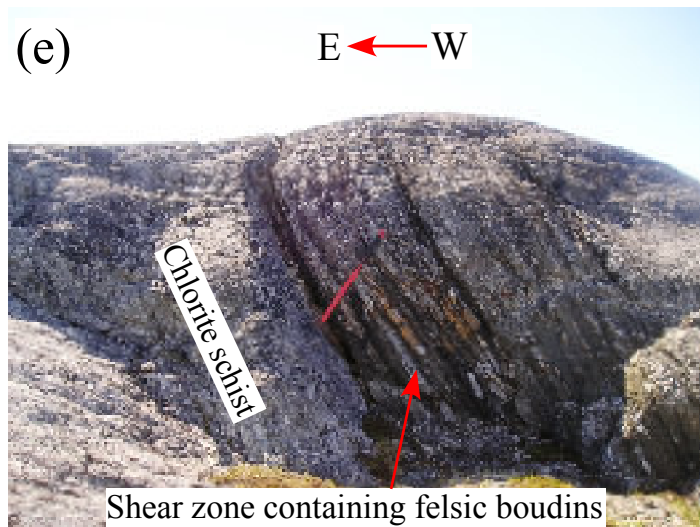
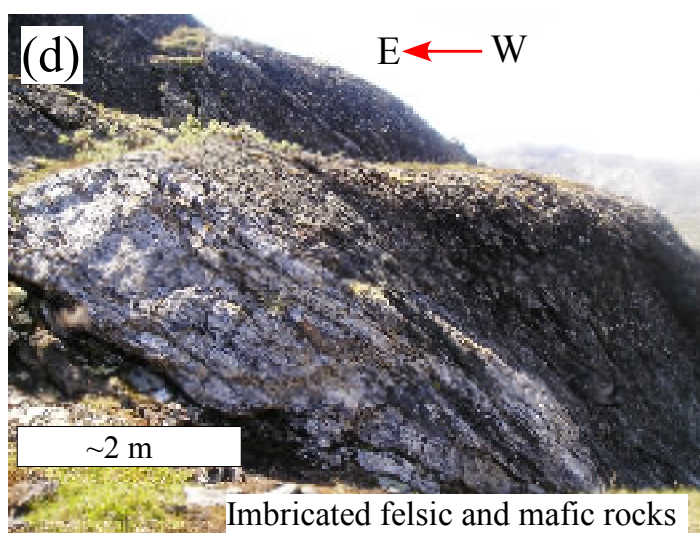




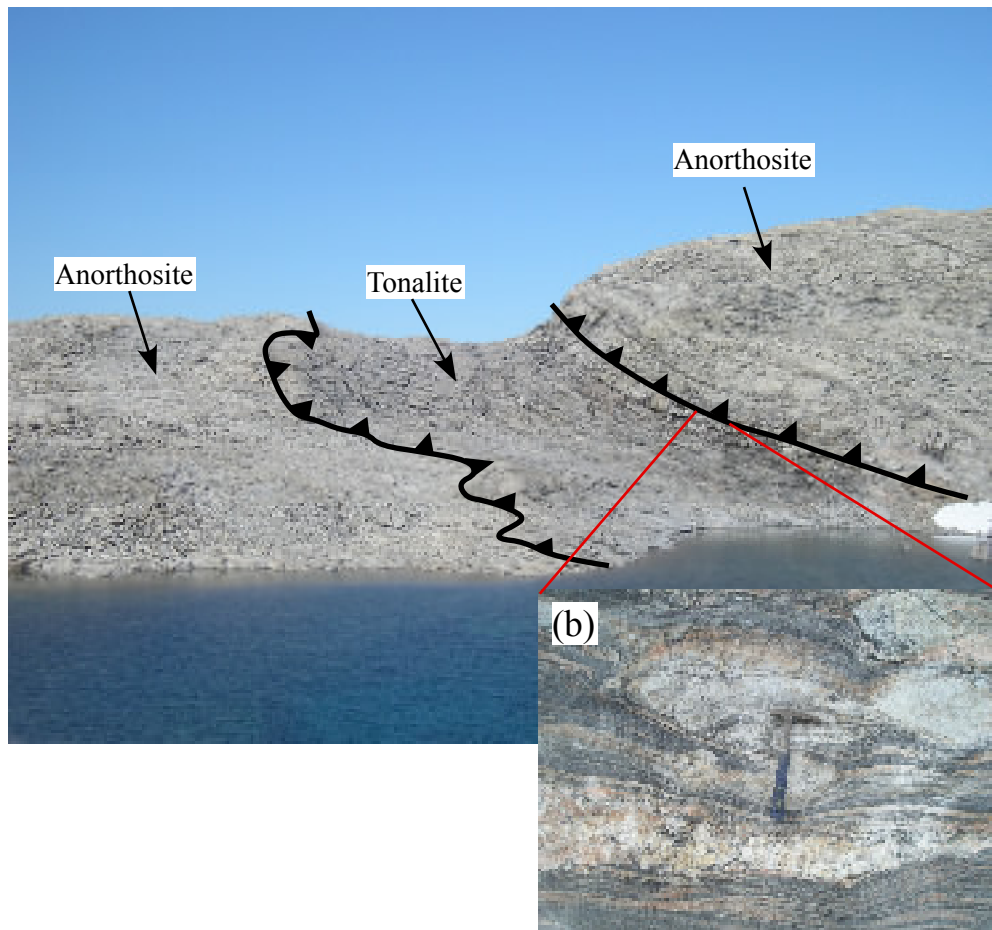




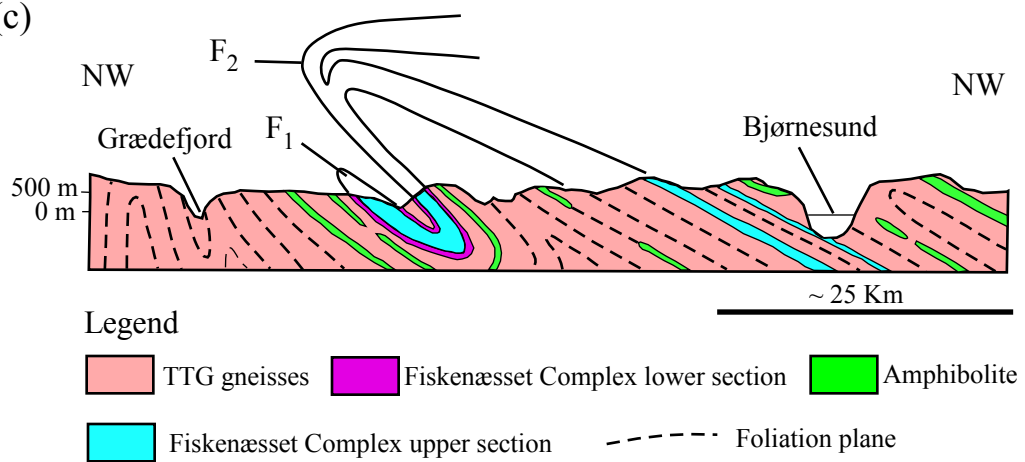


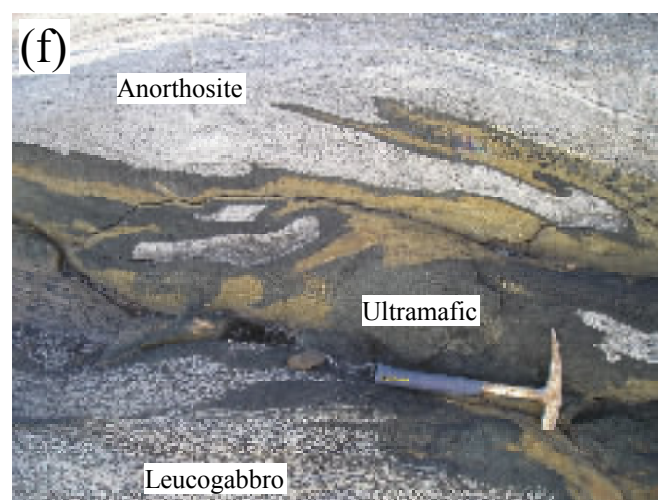
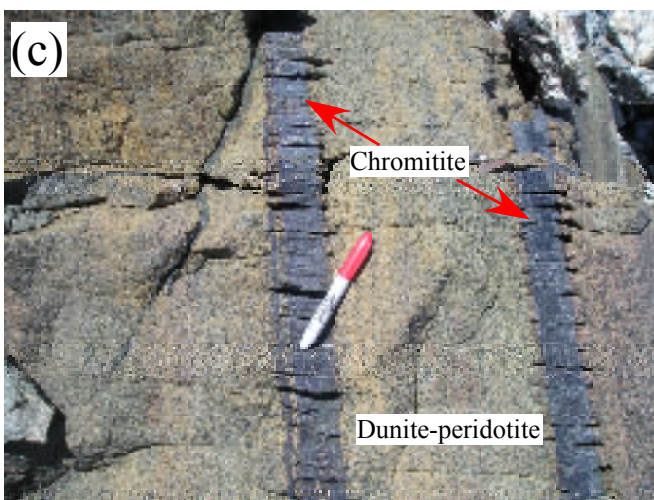
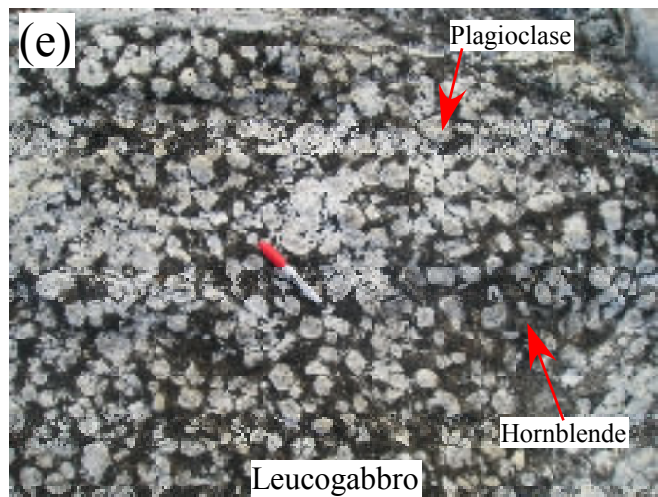
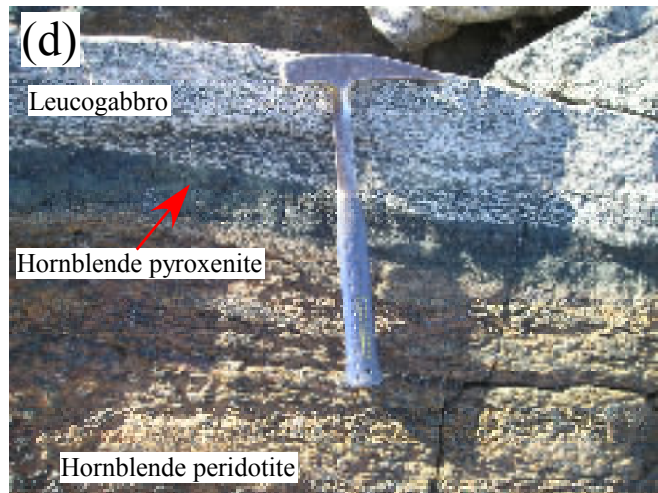
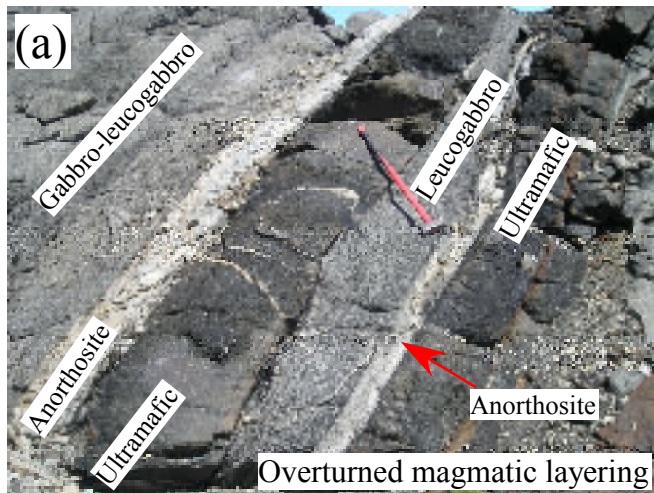


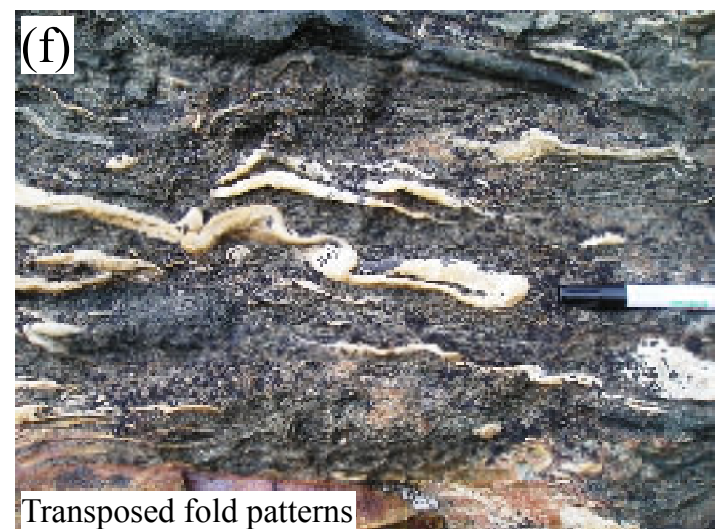
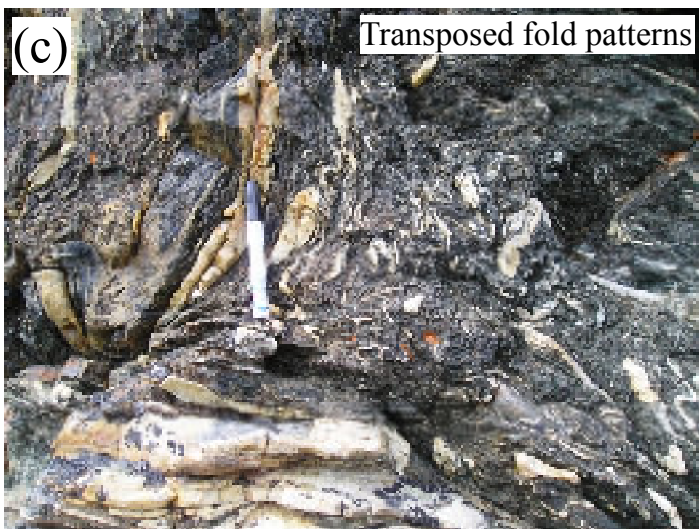
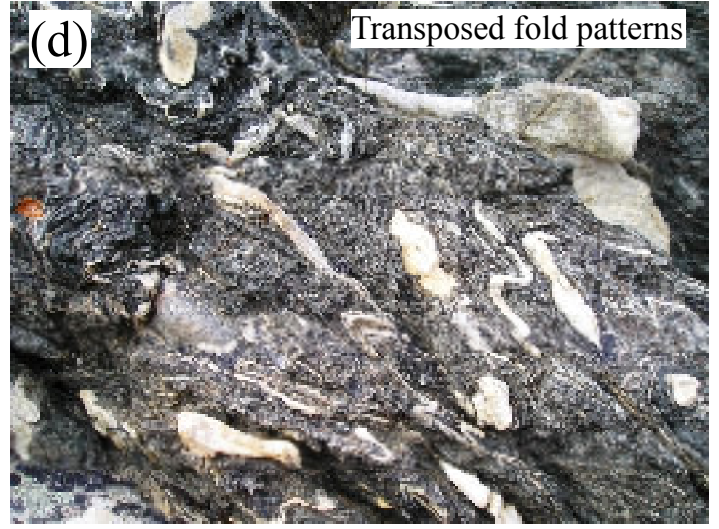
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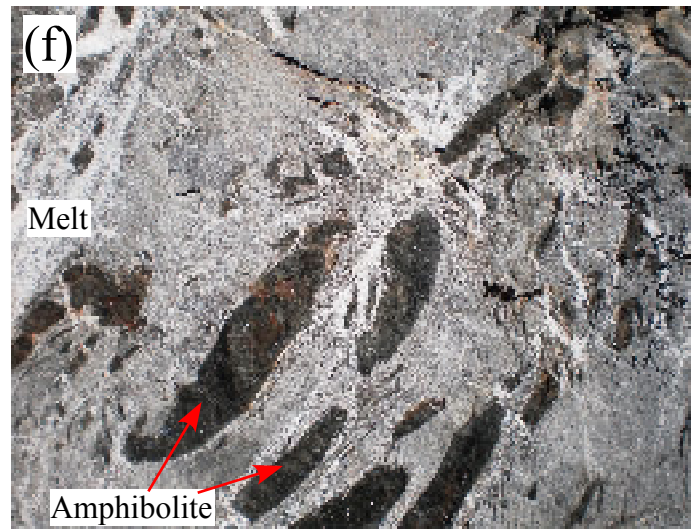
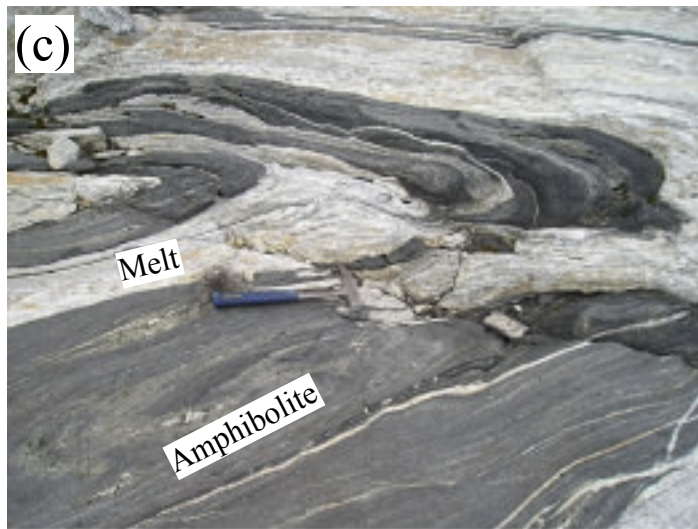
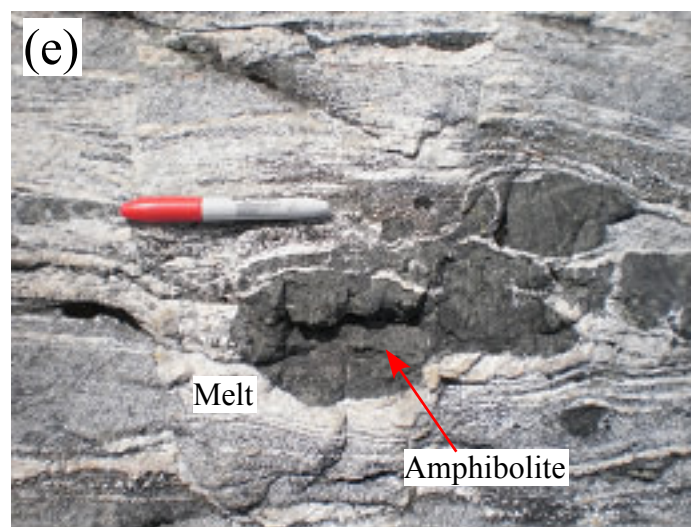
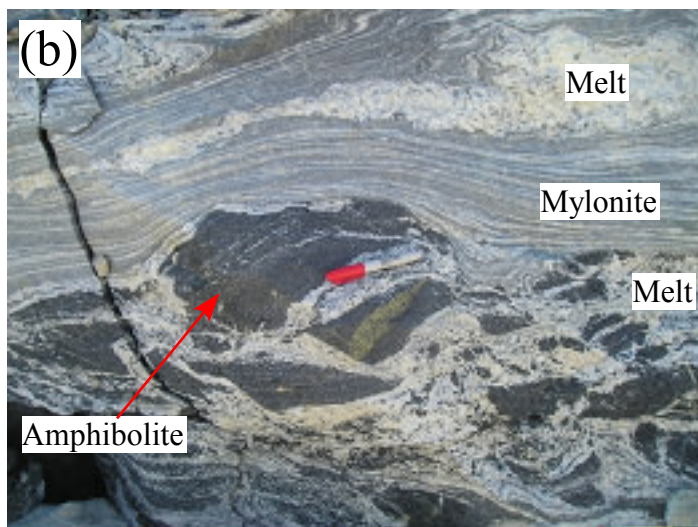
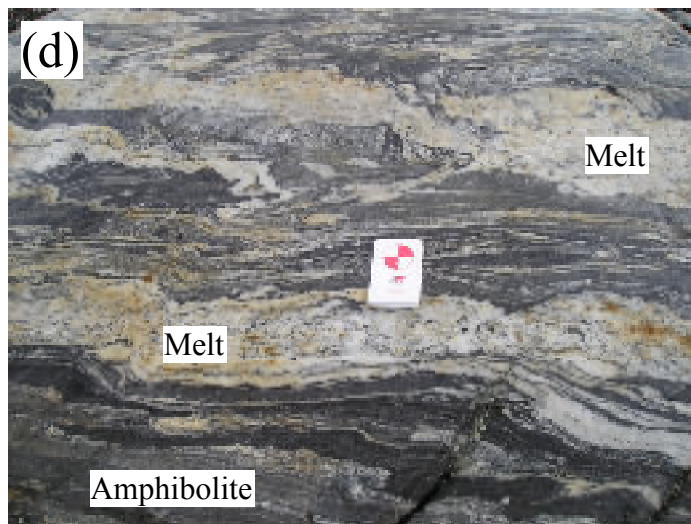
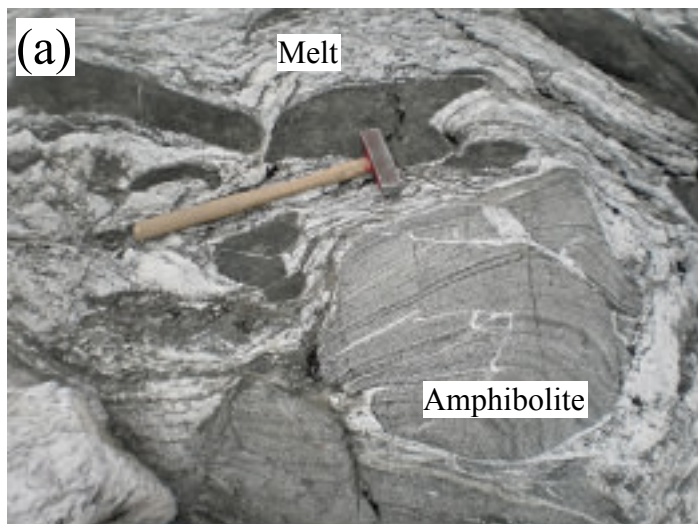


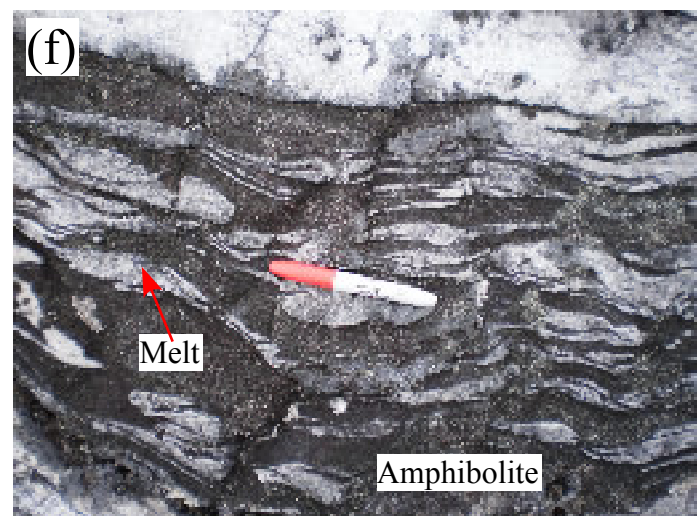
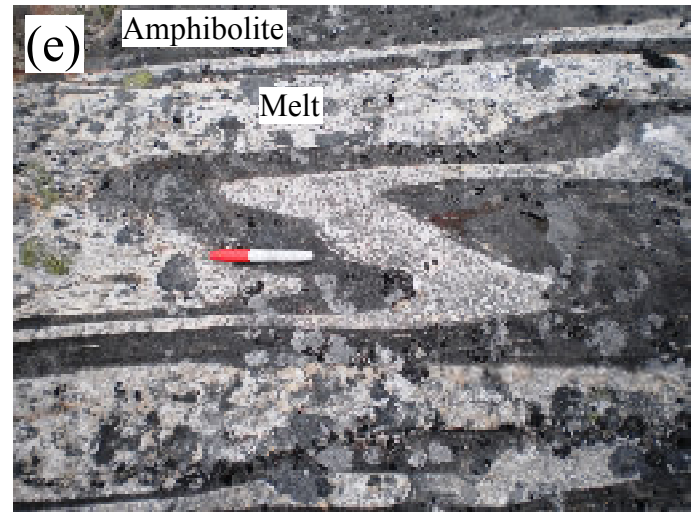
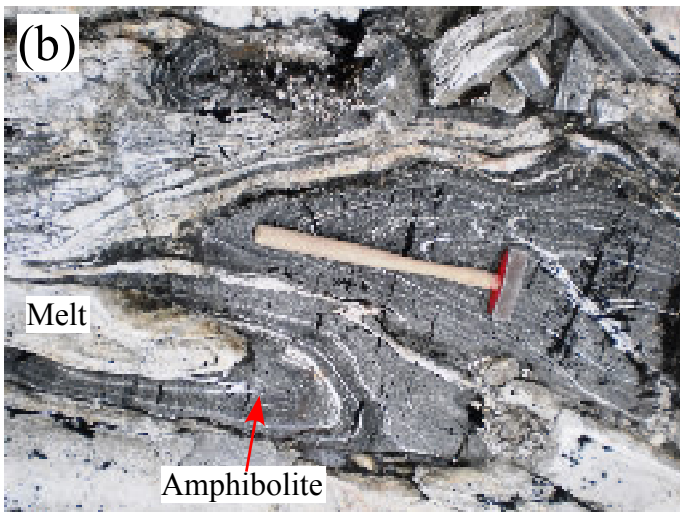
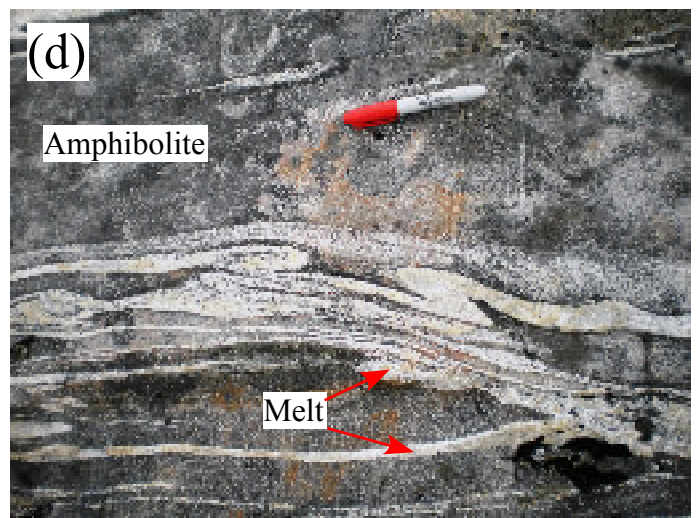
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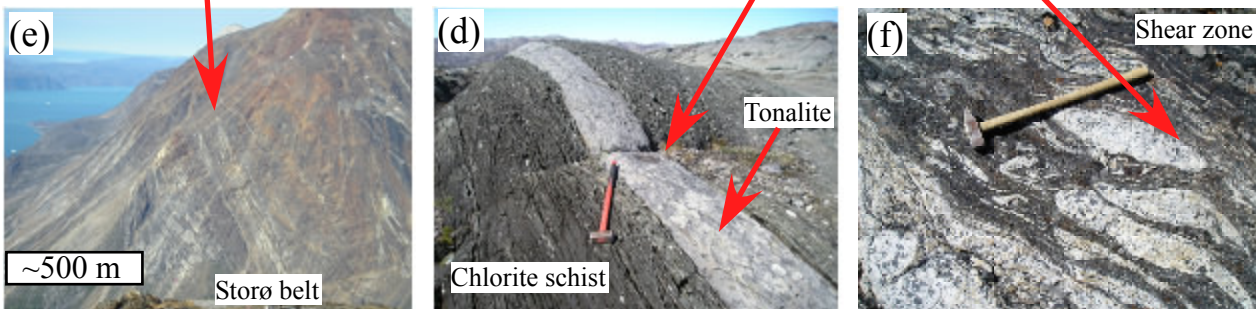
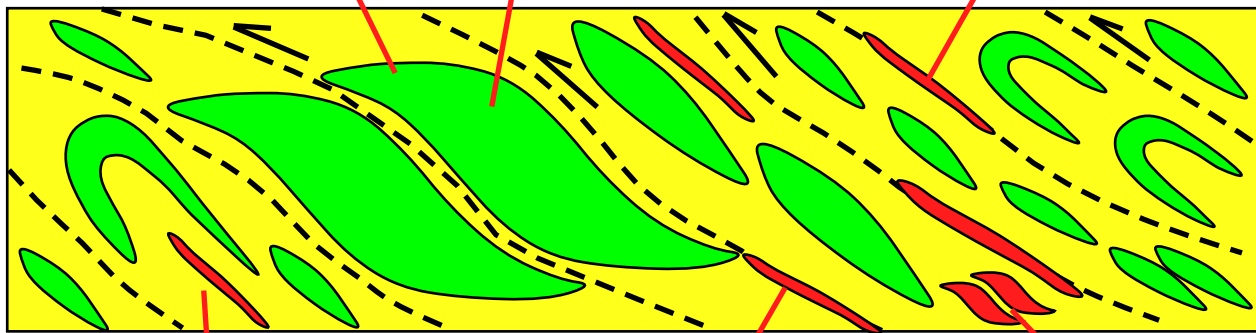
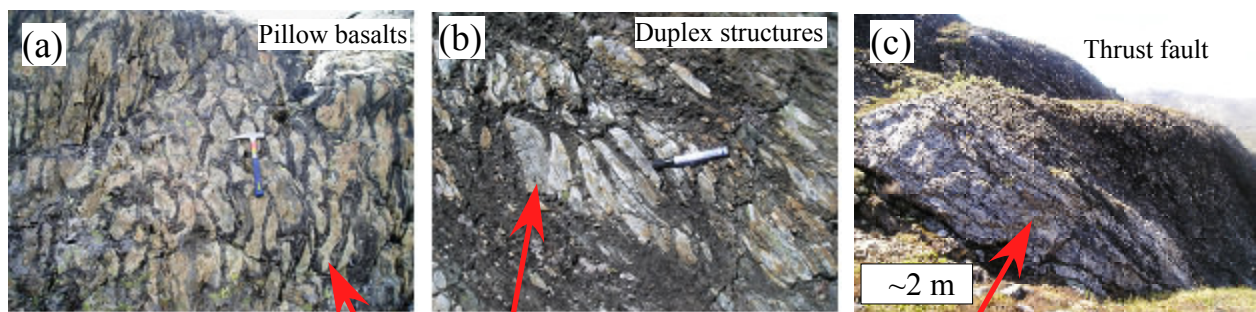
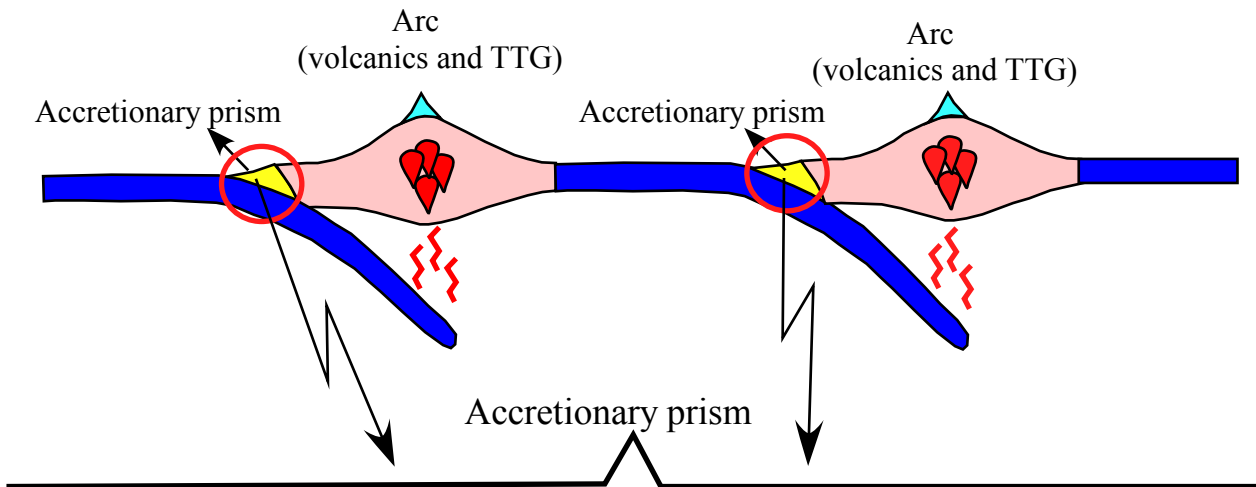




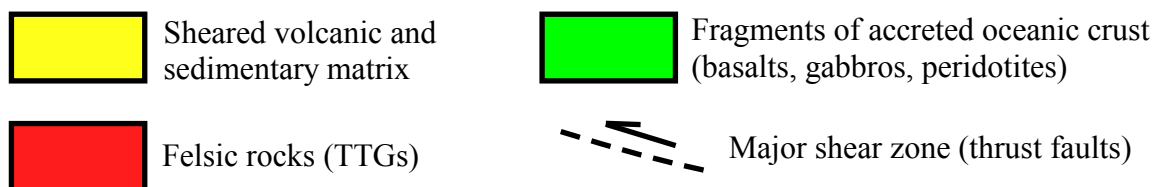


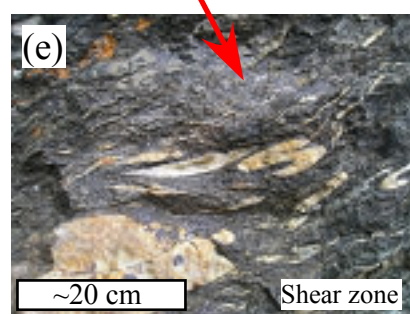
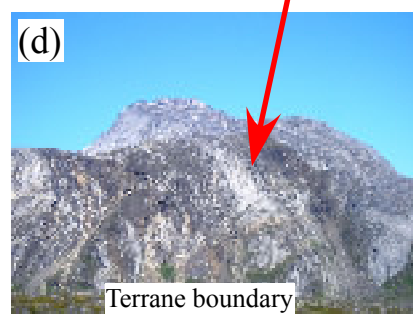
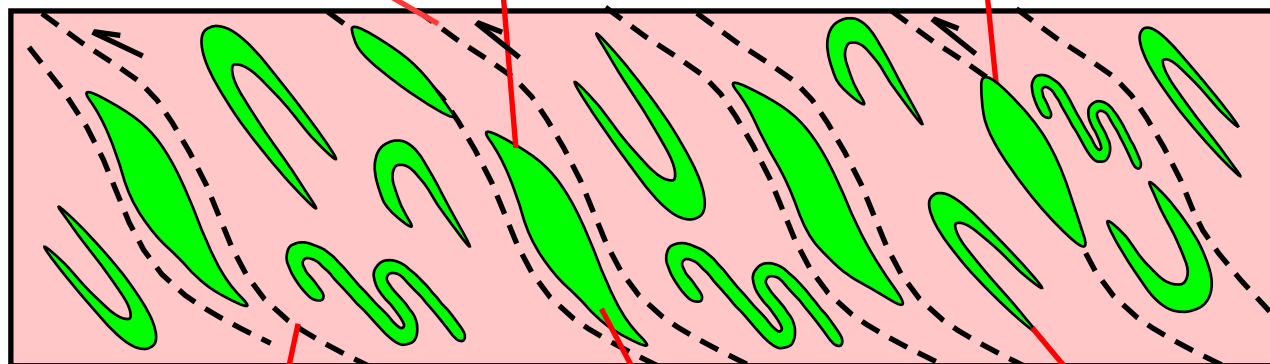
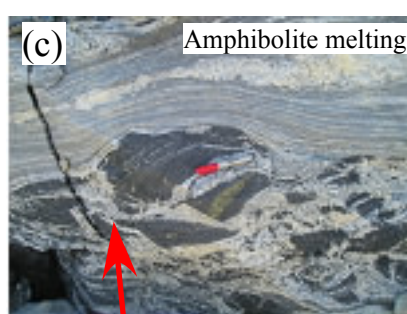
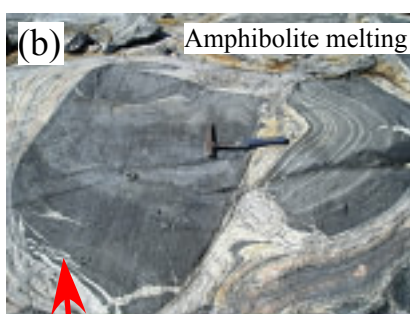
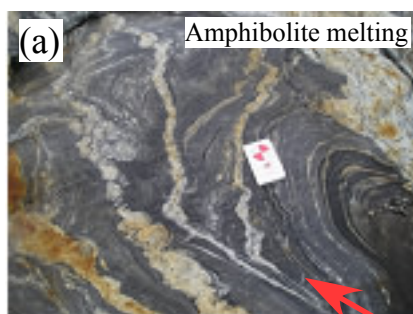
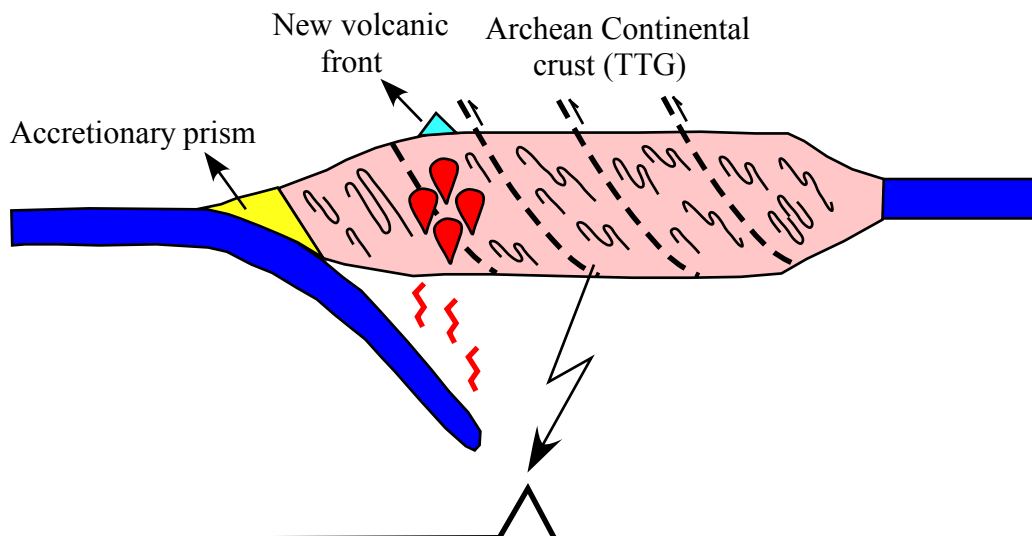




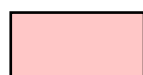


Legend





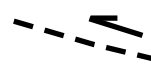
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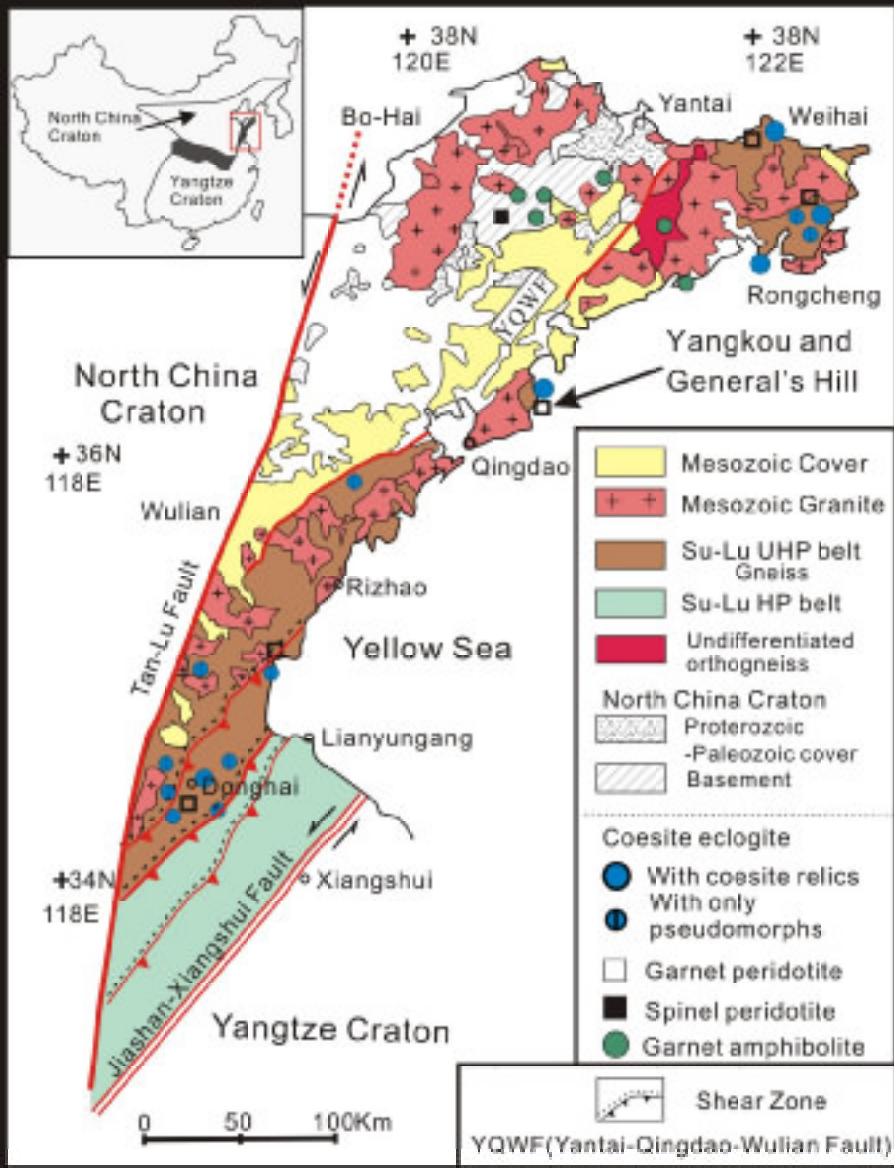
TTGs



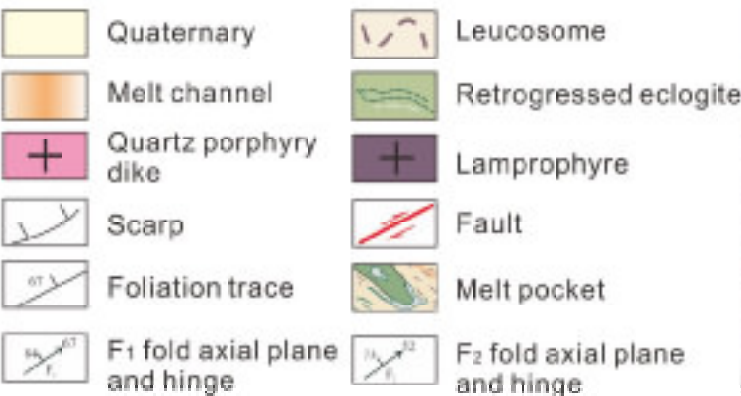
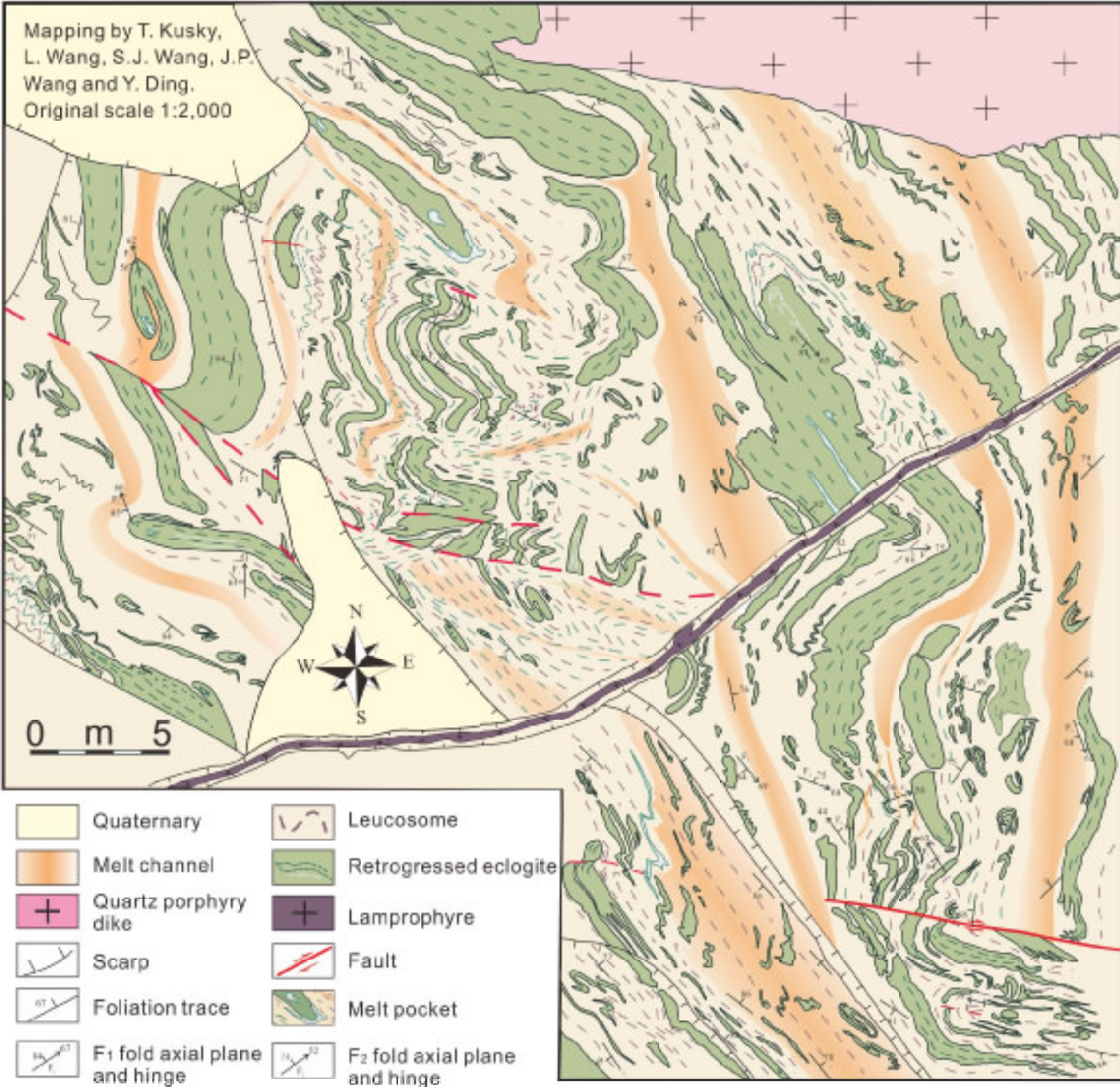
Supracrustal belts
(Greenstone belts)



Major shear zone
(thrust faults)



Mapping by T. Kusky,
L. Wang, S.J. Wang, J.P.
Wang and Y. Ding.
Original scale 1:2,000



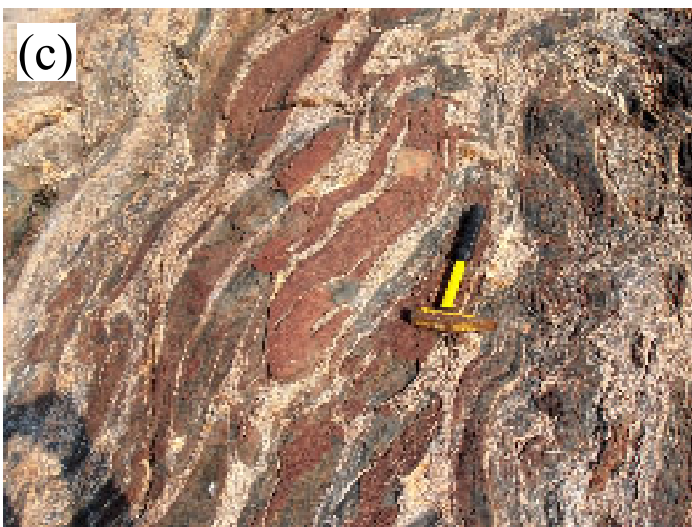
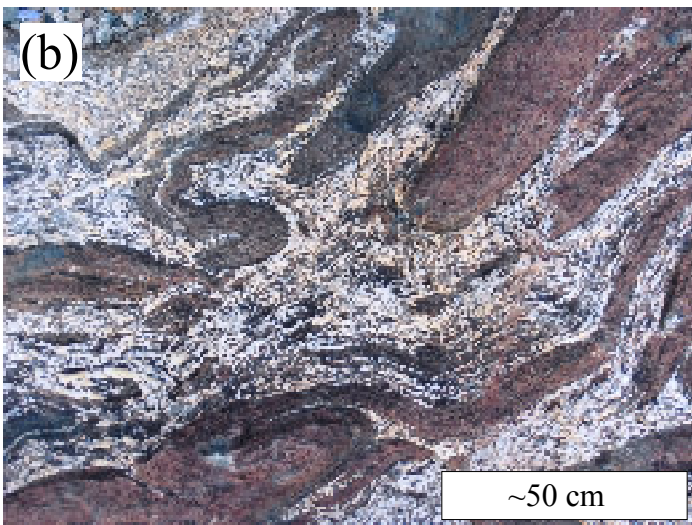
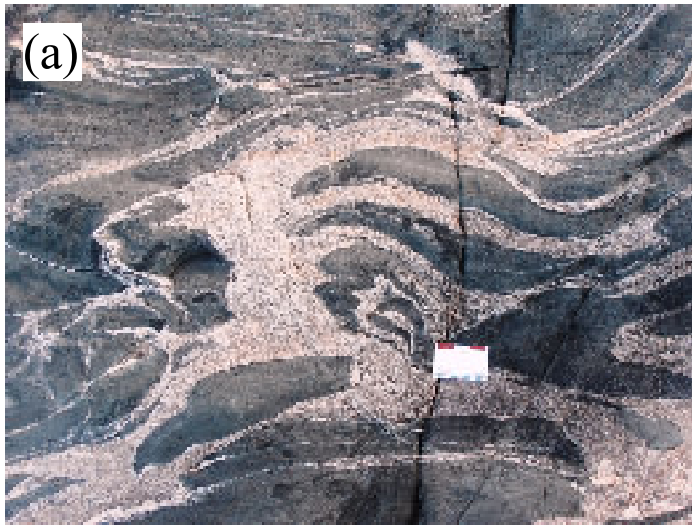


Table 1. A list of representative layered intrusions, oceanic plateaus, ophiolites, and continental flood basalts; and their age (Ma) and thickness (km).

Layered intrusions	Oceanic plateaus	Ophiolites	Continental flood basalts
Stillwater: 2700 Ma; ca. 6.5 km	Ontong Java: 120-90 Ma; 15-32 km	Oman (Semail): 96-90 Ma; 12-14 km	Keweenawan: 1100-1070 Ma; 8 to 15 km
Bushveld Complex: 2060 Ma 8-9 km	Manihiki: 120-125 Ma; 35 km thick	Troodos (Cyprus): 92-90 Ma; 6-6.5 km	Siberian traps: 250 Ma; 3.5 km
Skaergaard: 55 Ma; 2.5 km	Caribbean: 90-88 Ma; 20-22 km	Bay of Islands: 500-485 Ma; 8-9 km	Karoo traps: 180 Ma; 1.5 km
Great Dyke: 2575 Ma; >2 km	Hikurangi: 120 Ma; 10-15 km	Papua New Guinea: 71-65 Ma; 12-14 km	Parana traps: 120-140 Ma; 1.5 km
Kiglapait: 1300 Ma; 8-9 km	Shatsky Rise: 147 Ma; 10-28 km	Zambales-Coto: 45 Ma; 10 km	Deccan traps: 65-66 Ma; 1.5 km
Rhum: 60 Ma; 1.5-2 km	South Kerguelen: 110 Ma; 22 km	Duke Island: 108-111 Ma; 3 km	
	Central Kerguelen: 86 Ma; 19-21 km		

*Selected references: Wager and Brown (1968), Irvine (1974), Saleeby (1992), Kurth et al., 1998, Hawkins (2003), Mann and Taira (2004), Ernst et al. (2013)